5605/6/92
MARCH 992

CRITICAL EXAMINATION CORRELATIONS BETWEEN FRACTURE TOUGHNESS AND CHARPY IMPACT ENERGY - FINAL REPORT

For: A Group of Sponsors

By: R Phaal, K A Macdonald and P A Brown

WORLD CENTRE FOR MATERIALS JOINING TECHNOLOGY

CONTRACT SERIAL NO. 23440-9-9147-01-SQ

CONTRACTOR: THE WELDING INBTITUTE

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135 pp

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93-01536/

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EXECUTIVE SUMMARY

Background

The structural assessment of fusion welded plant requires fracture toughness to be known in terms of K, CTOD or J. However, toughness is often known only in terms of Charpy impact energy (or some other quality control based parameter). Many correlations have been developed between fracture toughness and simple measures of toughness, such as Charpy energy. This project has involved a critical review of published correlations, and the development of computer software for application of suitable correlations.

This project started in 1990, and was sponsored by 18 organisations (listed in Table 2 of the main text).

Objectives

1) Collect and review published correlations and establish their intended range of applicability and validity.

2) Test published correlations against a wide range of actual, measured fracture toughness data for various materials, to check independently their accuracy and, if possible, extend their range of applicability.

3) Provide IBM PC compatible software which will enable estimates of fracture toughness to be made for a specific material.

Conclusions

A total of 31 published correlations have been reviewed, of which 14 have not been previously reviewed in the literature. These correlations are summarised in detail in Appendix A.

A PC-based program (CvK) has been developed, to enable the efficient comparison, application and validation of published correlations. A total of 25 published correlations have been incorporated into CvK. In addition, TWI and user-defined data may be displayed, and correlations fitted to the data. Search facilities are provided for general and specific materials.

Twelve TWI data sets have been incorporated into CvK, to facilitate validation of the published correlations. The TWI data sets include data from various pressure vessel, pipeline, ship and offshore structural steels (parent plate, weld metal and HAZ). The codified 'lower-bound' correlations, such as those presented in BSI PD6493 and

ASME XI have been shown to be generally conservative, except for a 9% Ni pressure vessel steel (A553) and offshore structural steel HAZs (BS 4369).

Recommendations

The user data base facility in CvK provides an effective tool for the development and application of correlations for specific materials of interest to the user.

Financial

The income from participants was £90K, and this was all consumed in undertaking the project.

NOMENCLATURE

a,b,c,etc.	numerical constants
A	cross-sectional area
B	specimen thickness
B_o	side-grooved specimen thickness
CTOD	crack tip opening displacement
Cv	Charpy impact energy
$Cv_{pci,pi}$	pre-cracked instrumented Charpy impact energy
$Cv_{psb,sb}$	slow-bend pre-cracked Charpy energy
Cv_{us}	upper-shelf Charpy impact energy
Cv_i	initiation Charpy energy
Cv'	Charpy impact energy at shifted temperature
DBTT	ductile-to-brittle transition temperature
E	Young's modulus
FATT	temperature at which Charpy fracture surface has 50% ductile/brittle appearance
J_{Ic}	critical value of plane-strain J-integral
K_{Ic}	plane-strain fracture toughness
K_{Id}	dynamic fracture toughness
K_{Ia}	crack arrest fracture toughness
K_{IR}	reference fracture toughness (a lower bound to K_{Ic}, K_{Id} and K_{Ia})
K_c	fracture toughness
NDT	nil-ductility temperature
NDTT	nil-ductility transition temperature (T_{NDT})
P_{yy}	load required to cause ligament failure
P_f	load at fracture, from instrumented Charpy test
RT_{NDT}	reference toughness transition temperature
t	specimen thickness
T	temperature
$T_{0,100,91,28,ref}$,etc.	reference temperatures, see text for details
s	standard deviation
S	span of specimen
W	width of specimen
α	numerical constant
δ_c	critical CTOD

δ_i	initiation CTOD
$\phi\left(\frac{a}{W}\right)$	compliance function
ρ_o	notch root radius
σ_y	yield strength
σ_{yd}	dynamic yield strength
σ_f^*	microscopic cleavage stress
ν	Poisson's ratio

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1. INTRODUCTION

Fracture mechanics has proved to be an invaluable tool in many engineering applications, from the design of safe structures to the critical assessment of existing components. For a quantitative fracture assessment to be undertaken (such as is described in BSI PD 6493:1991 (1) and ASME XI (2)), the material toughness must be known in terms of K_{Ic}, the plane-strain lower-bound toughness, or alternatively in terms of fracture toughness (K_c), the crack tip opening displacement (CTOD) or the J-integral (J). For details on the meaning and development of these fracture toughness parameters the reader is referred to textbooks such as those by Broek (3) and Ewalds and Wanhill (4). Fracture parameters such as K_c, CTOD and J do not necessarily represent lower-bound toughness, and CTOD and J are more suited to the measurement of toughness in the transition and upper-shelf regimes, where the effects of crack tip plasticity may be significant.

A measure of fracture toughness may be obtained from several relatively simple tests, such as the Charpy V notch impact test, the drop weight test for measuring the nil-ductility transition temperature (NDTT) and the dynamic tear (DT) test. Of these, the Charpy impact test is the most popular, primarily due to its simplicity and cost effectiveness.

Owing to the simple, cheap and standard nature of Charpy tests, many correlations between fracture toughness and Charpy energy (Cv) have been developed. This report critically reviews the published correlations, and describes the development of a computer program which provides for implementation and comparison of the published correlations. In addition, facilities are provided for defining user data sets, to which correlation equations can be fitted. Supporting TWI data is provided.

The aims of the revised project proposal (5) were in general:-

i. Collect and review published correlations and establish their intended range of applicability and validity.

ii. Test published correlations against a wide range of actual, measured fracture toughness data for various materials to check

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independently their accuracy and, if possible, extend their range of applicability.

iii. Provide IBM PC compatible software which will enable estimates of fracture toughness to be made for a specific material.

This is the final report for project 5605. The critical literature review has been completed (6,7), and is included in this report as the bulk of the main text (excluding Section 6), and Appendix A. A PC based computer program has been developed which permits suitable published correlations to be applied effectively. TWI and user defined data may be displayed together with the correlations, permitting correlations to be compared and validated (and their ranges of applicability to be extended). This software is described in Section 6, and in detail in Appendix B, which is intended as a user guide.

The bulk of the correlations reviewed in this report are concerned with K_{Ic}-Cv correlations. It is not clear that all published K_{Ic} data are indeed valid, lower-bound plane strain values. Thus, such correlations should be treated with caution.

2. CHARPY AND FRACTURE TOUGHNESS TESTS

2.1. Comparison of Charpy and Fracture Toughness Tests

The standard Charpy V notch specimen consists of a 10x10x55mm notched bar, impact loaded in three-point bending by a pendulum striker. Charpy V specimen preparation and testing procedures have been standardised throughout the world - the most commonly used are BS EN 10045-1 (8) and ASTM E23 (9). Three parameters are commonly measured in such test procedures:

1) The energy absorbed by the specimen during the impact event.
2) The percentage crystallinity by area of the fracture surfaces.
3) The lateral expansion of the specimen.

In contrast, measurement of plane-strain fracture toughness, K_{Ic}, is more complicated as demonstrated in the two widely used testing standards, BS 5447:1977 (10) and ASTM E399 (11). Two specimen geometries are permitted:

1) the compact tension (CT) configuration, and
2) the single edge notched bend (SENB) specimen.

These specimens may be large, to ensure plane-strain conditions, and require a sharp notch, achieved by fatigue pre-cracking. A load-displacement trace of the test is also required to determine the crack initiation event. Owing to the more complicated requirement for the evaluation of K_{Ic}, such tests are generally an order of magnitude more expensive than Charpy impact testing.

The testing procedure for CTOD (BS 7448 (12) and ASTM E 1290 (13)) and J_{Ic} (ASTM E813 (14)) similarly involve expensive instrumented tests, requiring large specimens and post test analysis.

A simple measurement of toughness, such as the Charpy impact energy, Cv, may be sufficient for certain applications, such as quality control during a manufacturing process, or for purposes of material toughness comparison. Also, if the quantity of available material is limited, there might only be enough for Charpy testing, such as is the case in the nuclear industry where irradiation surveillance is necessary.

Many empirical correlations between Charpy impact energy, Cv, and fracture toughness, K_{Ic}, have been published in the literature in an attempt to establish a quantitative measure of fracture toughness, where the fracture toughness of a material is not known and where K_{Ic} testing is impracticable or unattractive. Pisarski (15) and Roberts and Newton (16) have reviewed most of the pre-1980 correlations, some of which have received considerable recognition, such as those of Barsom, Rolfe and Novak (17-19), Sailors and Corten (20), Marandet and Sanz (21) and the recommendations of BSI PD6493:1991 (1) and ASME III, Appendix G (22).

However, owing to substantial physical differences between the Charpy and K_{Ic} tests, the application of these correlations is uncertain, and so must be applied with caution. These difficulties stem from the following factors:

1) Notch acuity: The Charpy V notch root radius is 0.25mm, as specified by BS 131 and ASTM E23. On the other hand, BS 5447 and ASTM E399 require that CT and SENB K_{Ic} specimens must have a crack tip introduced by fatigue pre-cracking which is considerably sharper than the comparatively blunt notch of the Charpy specimen. Crack initiation is a function of the stress intensity at the crack tip, and so direct comparison between Charpy and K_{Ic} specimen crack initiation is difficult. In addition, differences in notch acuity modify the shape of the temperature transition curve (13).

2) Constraint: BS 5447 recommends that the thickness, B, and the crack length, a, of a CT or SENB specimen should be at least greater than $2.5(K_{Ic}/\sigma_y)^2$, and preferably greater than $4(K_{Ic}/\sigma_y)^2$. This condition ensures that a sufficiently high level of constraint is produced in order to generate plane-strain conditions at the crack tip, so that a lower bound toughness is obtained. Meeting this condition can result in large specimens. In contrast, Charpy specimens are small in thickness (10mm) and, in general, plane-strain conditions only occur at lower temperatures, in the lower-shelf regime.

3) Specimen size: As mentioned above, CT and SENB specimens are, in general, much larger than Charpy specimens. A crack tip of greater length is more likely to sample a locally brittle microstructure, increasing the probability that a lower-bound K_{Ic} is obtained, i.e. the greater the crack tip front length, the greater the chance of sampling a weakest link. In the case of Charpy specimens, either the notch must be very carefully positioned, or a statistically significant number of Charpy specimens must be used, to ensure that brittle zones are sampled. This is especially true for the heat affected zones (HAZs) in welds, where the microstructure may vary significantly with position. Even when a local brittle zone (LBZ) is sampled by the Charpy specimen, the total impact energy may not be significantly affected, due to notch acuity and initiation/propagation effects (see points 1 and 5).

4) Strain-rate: CT and SENB specimens are loaded quasi-statically for measurement of K_{Ic} (BS 5447 requires that the rate of increase of stress intensity factor immediately prior to crack initiation should be in the range 15 to 80$Nmm^{-3/2}$ s^{-1} corresponding to a strain-rate of the order 10^{-4} s^{-1} (22). On the other hand, Charpy specimens are loaded by impact, resulting in very high strain-rates, of the order 10^{-1} to 10^{2} s^{-1} (22). Yield strength is strongly dependent on strain-rate, and the consequence of this is that the Cv temperature transition curve, although similar in form to that of K_{Ic}, is shifted significantly to higher temperatures. The greater thickness and higher constraint in the K_{Ic} specimens may also shift the K_{Ic} transition curve to higher temperatures. Thus, for a given temperature, a CT or SENB specimen may fracture in a ductile mode, while a Charpy specimen might fracture in a cleavage mode. This effect is illustrated in Fig.1.

5) Initiation and propagation: K_{Ic} is a measure of material resistance to crack initiation (for ductile fracture modes, crack initiation is defined in the K_{Ic} standards by a small amount (2%) of crack growth). Charpy energy, Cv, is a measure of a mixture of fracture events of which the material's resistance to crack initiation and propagation are the primary features. For ductile fracture as little as 10% of the total Charpy energy may be associated with initiation, with 90% absorbed during propagation (24).

Bearing in mind these points, it might be expected that better correlation between K_{Ic} and Cv might be obtained for the lower-shelf, and possibly, transition regimes.

The uncertainties associated with K_{Ic}-Cv correlations are compounded by the fact that most of the correlations developed in the literature are not dimensionally consistent, since the underlying physical pro-

cesses are not fully understood, and the Charpy and fracture toughness tests may be measuring quite different fracture events. So, most of the correlations are empirical in nature, established by curve fitting to data. Also, the inherent scatter in both Charpy and fracture toughness tests, ensures that correlation between K_{Ic} and Cv is prone to uncertainty.

An increasing value of Charpy energy does not always imply increasing fracture toughness. For instance, Ritchie (23) has found that, for AISI 4340 steels, as the grain size increases, K_{Ic} increases, but Cv decreases. This effect was attributed to the differing response of the microstructure to the influence of notch acuity and is related to the austenitising temperature, on which the grain size is dependent. Also, yield stress would decrease with increasing grain size - this would reduce upper shelf toughness at least. This sort of effect cannot be accounted for by any of the currently available correlations.

2.2. Temperature Shift and Reference Techniques

Fracture toughness is strongly dependent on temperature for many ferritic materials. The fracture toughness and Charpy impact temperature transition curves are shifted from one another in terms of temperature, owing primarily to strain-rate effects, but also thickness and notch acuity effects. So, many of the published correlations employ temperature shift or temperature referencing concepts (19,22,25-26). Temperature shift behaviour is illustrated in Fig.1.

These methods involve either referencing the fracture toughness temperature transition curve in terms of some parameter measured from simple tests such as the Charpy impact test or the Pellini drop weight test; or correlating fracture toughness directly to Charpy impact energies, but with a temperature shift separating the two tests. Both of these techniques can involve several Charpy specimens, and so their general application is not always possible.

Several referencing temperatures are commonly used, some of which are purely empirical curve fitting parameters, while others have more physical meaning.

The ductile-to-brittle transition temperature (DBTT) is often used to reference the Charpy temperature transition curve to that of fracture toughness. The DBTT is commonly defined as the nil-ductility transition temperature (NDTT), as per ASTM E208 (36) for Navy application, and as the reference nil-ductility transition temperature (RT_{NDT}) for nuclear pressure vessel application (ASME III (22)). ASME III Appendix G refers to section NB-2330 of the ASME Code where RT_{NDT} is defined. Firstly, the reference temperature RT_{NDT} ($\geq$NDTT) is

determined by drop weight testing. At a temperature not greater than NDTT +33°C each Charpy test must result in a lateral expansion of ≥0.89mm and an impact energy of ≥68J. If these conditions are not met, then additional tests may be performed to determine T_{Cv} (temperature at which lateral expansion = 0.89mm and Cv = 68J). RT_{NDT} as the higher of NDTT and T_{Cv} -33°C.

Yukawa and Merkle (37) have reviewed the development of the reference fracture toughness procedures (described in Section 4.2 and shown in Appendix A.2.4) implemented in the ASME III Boiler and Pressure Vessel Code, originally developed by a PVRC committee (detailed elsewhere in this report). These reference toughness (K_{IR}) procedures are based on a correlation which is a lower bound to static, dynamic and crack arrest toughness (based on data obtained principally from nuclear pressure vessel steels - A508 and A533B). The authors (37) comment that more than 10 years has elapsed since these reference toughness curves were developed, and although most data that have been generated since then indicate that this approach is conservative, several factors concerning the use of the reference indexing temperature RT_{NDT} have been noticed:

1) RT_{NDT} does not adequately adjust for differences among materials. In some cases it has been shown that correlations based on this temperature shift concept are worse than if no temperature shift were applied.

2) The use of RT_{NDT} does not take into account differences between slopes of the transition region of the fracture toughness and Charpy temperature transition curves.

3) The reference toughness curve, shown in Appendix A.2.4 Fig.A.2.4.1, which is an exponential function, does not show any limiting toughness values for higher temperatures, owing to a lack of data during the original development of the method.

4) The statistical relevance of the lower-bound reference toughness curve is of an unknown confidence level.

These last two points have been addressed in the literature (25-27) The level of computational complexity required in order to address these points is so great as to require computing power to take full advantage. Appendix A.6.2 describes the complex form of both the experimental and tanh curves.

Barsom (28) has presented a technique for relating the static fracture toughness, K_{Ic}, to the Charpy impact energy, Cv, in the transition regime, accounting for strain rate effects by shifting the temperature transition curves (see Appendix A.3.3):

$$\Delta T = 119 - 0.12\,\sigma_Y \quad [°C, N/mm^2] \qquad [1]$$

which is claimed to be valid in the range $250 < \sigma_Y < 965 N/mm^2$ and $\Delta T = 0°C$ for $\sigma_Y > 965 N/mm^2$.

Marandet and Sanz (21), Oda (32) and Kanazawa et al (31) have also employed temperature shift concepts to relate the dynamic fracture toughness, K_{Id}, to the static K_{Ic} (see Appendix A.3.2, A.3.4 and A.4.2).

3. NON-STANDARD CHARPY TESTS

In order to overcome the difficulties associated with strain-rate effects, notch acuity and constraint, etc., various correlations have been proposed relating fracture toughness to Charpy energy obtained from non-standard Charpy specimens. These include:

1) Side-grooved specimens (23,38-43)
2) Non-standard sized specimens (42,44,45)
3) Quasi-static three-point bend specimens (16,40,42,43,46-53)
4) Fatigue pre-cracked specimens (16,40,42,43,46-53)
5) Instrumented impact specimens (16,51,54-62)
6) Various combinations of the above

Since testing procedures for non-standard Charpy specimens have not been formalised in codes, correlations based on these procedures should be used with caution, following the recommendations of the original reference.

Fatigue pre-cracked Charpy specimens have been used to circumvent the difficulties associated with notch acuity (16,40,42,43,46-53). Most of the tests that use pre-cracked Charpy specimens also involve other non-standard procedures, such as slow-bend, instrumented pendulum or side-grooved specimens, and so these have not been reviewed in detail in this report.

Charpy specimens have been loaded quasi-statically in a slow-bend configuration to minimise the effects of inertia and strain rate (16, 40,42,43,46-53). One of the main advantages of using standard Charpy specimens to estimate fracture toughness is the simplicity and standard nature of the impact test. However, slow-bend Charpy tests are as complicated and expensive as standard CT and SENB K_{Ic} fracture toughness testing (ASTM E399 and BS 5447), and so there appears to be little advantage in using slow-bend Charpy specimens other than their smaller size.

In an effort to quantify the effects of impact loading, instrumented Charpy tests have been developed (16,51,54-62). These methods usually involve strain gauging the impact pendulum, and analysing the load-

time-displacement traces to achieve a better understanding of strain rate and inertial effects, and hence to better correlate Charpy impact parameters and K_{Ic}. These procedures require sophisticated instrumentation, and interpretation of results is difficult especially as the strain gauge readings are prone to severe noise corruption and must be filtered. State of the art instrumented drop weight testing machines can ameliorate these effects.

Side-grooved Charpy specimens have been used to increase the constraint at the notch tip, in attempts to improve the correlation between Charpy energies, Cv, and the plane-strain fracture toughness, K_{Ic} (23,38-43).

Various other non-standard Charpy tests have been developed, including the use of laminated Charpy specimens (63), and the use of the Hopkinson pressure-bar as an alternative to the instrumented pendulum, to reduce noise (54). Investigations on R-curve toughness testing, using pre-cracked, slow-bend Charpy specimens have been carried out (47,48). Other authors (42,52) discuss the use of equivalent energy approaches for determining fracture toughness from pre-cracked slow-bend Charpy specimens. Robinson and Tetelman (53) have investigated the correlation between fracture toughness and various non-standard parameters obtained from pre-cracked slow-bend Charpy specimens. These included the CTOD, NRC (lateral notch root/crack tip contraction), angle of bend, stretch zone, J-integral, and equivalent energy. Their work (53) demonstrated that the use of angle of bend, stretch zone and equivalent energy produced poor correlations, and the reader is referred to their paper for details.

4. THE CORRELATIONS

The correlations between Charpy energy and fracture toughness which have been reviewed in this report are to be found in Appendix A. Each correlation has been summarised, and where possible, each summary presents the following information.

1) The correlations, which have been expressed in the form and units presented in the literature.

2) The materials for which the correlations have been derived. If these materials included data from welded joints, then attention has been drawn to this fact.

3) The number of data points from which the correlations have been derived.

4) The temperature, Charpy energy and yield strength ranges over which the correlations are considered to be valid by the authors.

The correlations which have been reviewed, have been broadly separated according to the temperature transition curve regime to which they apply; lower-shelf, lower-shelf/transition, transition, transition/upper-shelf, upper-shelf and lower-shelf/transition/upper-shelf. It is not always clear from the literature to which regime the correlation is applicable, and so these correlations have been grouped together in Appendix A under the heading 'Other Correlations'.

Most of the correlations which have been developed before 1980 have been reviewed previously by Pisarski (15), Roberts and Newton (16), Graville (64) and Hertzberg (65). So as not to repeat their work, the reviews (15,16,65) have been compiled to form the summaries of most pre-1980 correlations in Appendix A. Some of these correlations are much referenced in the literature, such as those due to Barsom, Rolfe and Novak (17-19,28), Sailors and Corten (20), and Marandet and Sanz (21), as well as those recommended by ASME III (22) and BSI PD6493:1991 (1).

In this section the correlations, which are detailed in Appendix A, will be introduced by presenting the generic form of each correlation. This approach is useful in distinguishing between the various correlations which have a similar form, with constants determined either by the material data from which they are derived, and by the confidence level to which the correlations are applied.

Note that universally adopted symbol definitions are given in the Nomenclature and that specific definitions are included in the relevant section of Appendix A.

4.1. Lower-Shelf Correlation

The only correlation which has been identified that applies specifically to the lower-shelf regime is that of Chaudhuri et al (66) which has been derived from data from weldments in pipeline steel (see Appendix A.1.1):

$$\log \delta_c = a + b \log Cv \qquad [2]$$

This correlation relates the Charpy impact energy to fracture toughness expressed in terms of critical CTOD. A similar relationship may apply to K_{Ic}-Cv correlations as the generic form of Eq.[2] is also used to describe K_{Ic}-Cv correlations (see Eq.[3] below).

4.2. Lower-Shelf/Transition Correlations

Several of the correlations that have been developed for the lower-shelf and transition regimes (16,20) are of the form (see Appendix A.2.3):

$$K_{Ic} = a\ Cv^{b} \qquad [3]$$

These correlations have been derived principally from data of Barsom, Rolfe and Novak (17-19), and these original correlations are discussed in the next section. Sailors and Corten (20) reduced the range of Charpy impact energies over which the correlation was applicable, to reduce the influence of the upper-shelf, and to improve the correlation. Roberts and Newton (16) have compared various correlations of this form, and have derived correlations which form a lower bound to these (included later in Section 5).

The PVRC (29) and ASME III (22) recommend correlations for A533B and A508 of the form (see Appendix A.2.4):

$$K_{IR} = a\ \exp(b\ (T - NDT + c)) + d \qquad [4]$$

where K_{IR} is the reference fracture toughness, a lower bound to static, dynamic and crack arrest toughness (K_{Ic}, K_{Id}, K_{Ia}). NDT is the nil-ductility temperature, which can be measured using drop-weight tests. These correlations are applicable to a range of low to medium strength steels. A correlation similar to that of Eq.[4] have been developed by Matsumoto et al (30), derived from data from JIS SM41B and SM50 steel plate, including electroslag welds (see Appendix A.2.5):

$$K_{Ic} = a + b\ \exp(c\ (T - FATT + d)) + e \qquad [5]$$

where FATT is the fracture appearance transition temperature at which a Charpy specimen has a 50% shear fracture appearance.

Tetelman et al (67) have derived a correlation of the form (see Appendix A.2.1):

$$K_{Ic} = a\ \sigma_y \left(\exp\left(\frac{\sigma_f^*}{\sigma_y} - 1\right) - 1\right)^{\frac{1}{2}} \rho_o^{\frac{1}{2}} \qquad [6]$$

where σ_f^* and ρ_o are parameters associated with the microstructure near the crack tip.

Barsom (28) has developed a correlation of the form (see Appendix A.3.3):

$$K_{Ic}^2 = a\ E\ Cv \qquad [7]$$

These correlations were based on various standard and non-standard Charpy specimens, and were derived from data from the literature for a variety of materials (17-19). Barsom also developed a temperature shift relationship, to account for strain rate effects:

$$\Delta T = a + b\ \sigma_y \qquad [8]$$

Imai et al (68) have developed a correlation which is applicable to 9%Ni steel and welds, and which represents a lower-bound fit to over 65 data points (see Appendix A.2.6):

$$\frac{K_{Ic}^2}{\sigma_y} = a\ Cv^{\frac{1}{2}} \qquad [9]$$

4.3. Transition Correlations

Barsom et al (17-19) have developed a correlation which is applicable to the transition regime, and which has the form (see Appendix A.5.1):

$$K_{Ic}^2 = a\ E\ Cv^b \qquad [10]$$

These correlations have been derived from data for various low, medium and high strength steel alloys. Other authors (16,21,69) have developed correlations which are similar to that of Eq.[10], and have the form (see Appendix A.3.1 and A.3.4):

$$K_{Ic}^2 = a\ Cv^b \qquad [11]$$

This correlation has also been derived from data of various low, medium and high strength steel alloys. Marandet and Sanz (21) and Roberts and Newton (16) have incorporated a temperature shift relationship to account for strain rate effects (see Appendix A.3.4):

$$T_i = a\ T_j + b \qquad [12]$$

where T_i is the temperature at which K_{Ic} = i, MPa.$m^{\frac{1}{2}}$ or ksi.$in^{\frac{1}{2}}$, and T_j is the temperature at which Cv = j, J or ft.lb. Roberts and Newton

(16) point out that various relationships of the form of Eq.[12] based on different reference temperatures T_i and T_j are equally valid (see Appendix A.3.4). This ambiguity is typical of empirically-based correlations, which do not generally have sound physical reasoning behind them.

Kanazawa et al (31) have developed a temperature shift relationship for various medium strength steels, including welds and which may be used in conjunction with other correlations, such as those represented by Eq.[10] and [11] (see Appendix A.3.2):

$$\Delta T = (R - 1)\ FATT + at^{\frac{1}{4}} + b \qquad [13]$$

$$\text{where } R = c\ \sigma_y + d \qquad [14]$$

FATT is the temperature at which the Charpy fracture surface has a 50% ductile/brittle appearance, and t is the plate thickness for which this relationship was derived.

The National Materials Advisory Board (NMAB) have presented a correlation which relates the load at failure (P_f) from an instrumented Charpy V notch impact test to the dynamic fracture toughness, K_{Id}, for low to medium strength steels (70) (see Appendix A.7.4):

$$K_{Id} = a\ P_f \qquad [15]$$

4.4. Transition/Upper-Shelf Correlations

Thorby and Ferguson (71) have proposed a correlation of the form (see Appendix A.4.1):

$$K_c = a\left(\frac{Cv}{A}\right)^b \qquad [16]$$

This relationship was derived from limited data for medium strength steels. Oda (32) has developed four correlations for medium to high strength steels and an aluminium alloy (see Appendix A.4.2). For fractures which are brittle in nature, correlations are of the form:

$$\delta_c = a\ \ln\ (b\ Cv'/\sigma_y) \qquad [17]$$

$$\delta_c = a\ \{\ln\ (E\ Cv'/\sigma_y^2)\}/E \qquad [18]$$

while for fractures which are ductile in nature:

$$\delta_c = a\ Cv'/\sigma_y + b \qquad [19]$$

$$\delta_c = a\ Cv'/\sigma_y + b\ \sigma_y/E \qquad [20]$$

where Cv' is the Charpy impact energy at a temperature obtained from a temperature shift of the form:

$$\Delta T = {}_vT_{RS} - T_f \qquad [21]$$

where ${}_vT_{RS}$ = FATT, the temperature at which the Charpy fracture surfaces have a 50% ductile/brittle appearance.

Various correlations between the nil-ductility transition temperature (NDTT) and fracture toughness have been proposed (16-19,33,34,72) of the form:

$$K_{Id}\ (NDTT) = a\ \sigma_{yd} \qquad [22]$$

where K_{Id} is the dynamic fracture toughness, evaluated at the NDTT, and σ_{yd} is the dynamic yield strength. Rolfe et al (17-19) have shown that the quasi-static yield strength may be related to the dynamic yield strength as follows:

$$\sigma_{yd} = \sigma_y + a \qquad [23]$$

These correlations have been summarised in Appendix A under the heading 'NDTT Correlations' (Appendix A.4.3).

4.5. Upper-Shelf Correlations

Many authors (16-19,73,74) have developed upper-shelf correlations of the form (see Appendix A.5.1, A.5.2 and A.5.4):

$$\left(\frac{K_{Ic}}{\sigma_y}\right)^2 = a\left(\frac{Cv}{\sigma_y} + b\right) \qquad [24]$$

These correlations are applicable to medium and high strength steels. The correlation of Ault et al (73) is specifically for high strength steels, while that of Priest et al (74) includes data from welds. Roberts and Newton (16) have fitted lower-bound correlations to published data (17-19).

Norris et al (24) have developed a correlation between Charpy energy and fracture toughness in the form of the J-integral, J_{Ic}, of the form (see Appendix A.5.3):

$$J_{Ic} = Cv\left(\frac{\sigma_y + a}{b}\right) \qquad [25]$$

This correlation has been derived from data on medium to high strength steels. Witt (52) has developed two correlations which are applicable to various medium strength steels, including manual metal arc (MMA) and submerged arc (SA) welds (see Appendix A.5.5):

$$K_{Ic} = a\ Cv + b \qquad [26]$$

$$K_{Ic} = (a\ Cv + b)^2 \qquad [27]$$

4.6. Lower-Shelf/Transition/Upper-Shelf Correlations

Begley and Logsdon (75) have developed a correlation which is applicable over the entire transition curve temperature range. Their correlation consists of four straight-line segments which approximate the shape of the true temperature transition curve. They (75) have used the upper-shelf correlation of Barsom, Rolfe and Novak (17-19) to define the upper-shelf portion of their discrete temperature transition curve. The reader is referred to Appendix A.6.1 for details of this correlation.

A number of authors (25-27,35) have developed correlations based on an hyperbolic tangent (tanh) function, which approximates the entire temperature transition curve (see Appendix A.6.2 and A.6.3):

$$K_{IR} = a + b\ \tanh\left(\frac{T - T_o}{c}\right) \qquad [28]$$

where a, b, c and T_o are curve fitting parameters, and K_{IR} is the reference fracture toughness, a lower bound to K_{Ic}, K_{Id} and K_{Ia}. A similar tanh function may be used to describe the Cv temperature

transition curve. The correlation of Richardson et al (35) is applicable to pressure vessel steels, including MMA and SA welds. Oldfield et al (25,26) and Wullaert et al (27) have developed a series of correlations of the form of Eq.[28], based on statistical curve fitting principles. These correlations are based on more than 100 data points from nuclear pressure vessel steels (A533B and A508), mostly from the transition and upper-shelf regimes. They have assumed a lower-shelf K_{IR} value as a lower bound to the limited lower shelf data which they had, reducing Eq.[28] to a three-parameter form, see Fig.A.6.2.3 in Appendix A.

These statistical approaches (25-27,35) represent a significant advance in the ability to predict fracture toughness from Charpy tests to a given level of confidence over the entire temperature transition curve. However, these correlations have become sufficiently complex so that, if full advantage is to be gained from them, the procedures must be automated, and computer software developed.

Girenko and Lynden (76) have developed several correlations which are of the form (see Appendix A.6.4):

$$K_{Ic} = \left(a \frac{E}{1 - \nu^2} \frac{Cv}{A}\right)^{\frac{1}{2}} + b \qquad [29]$$

These correlations are applicable to both brittle and ductile fracture modes, and are based on more than 100 data points for low, medium and high strength steels, including weldments.

BSI PD6493:1991 (1) recommends that, for the purposes of flaw assessment, K_{Ic}-Cv correlations should only be used when direct measurement is not possible. However, two pessimistic correlations are presented which are applicable to a large range of steels, including weld deposits. The first correlation applies to the lower-shelf and transition regimes, while the second applies to the upper-shelf to ensure that fracture toughness is not overpredicted by high Cv energies in this region. Both correlations are presented in graphical form only (see Appendix A.6.5).

The lower shelf/transition regime correlation of PD6493 relates K_{Ic} to the temperature difference between the operational temperature and the temperature for a Cv energy of 40J. Although it is not specifically stated in the document, it is clear that the 40J transition temperature is assumed equivalent to the NDTT (and this PD6493 correlation is thus equivalent to the ASME/PVRC correlation described in Appendix A.2.4). Graville (64) and Pisarski (15) have questioned this equivalence. Graville has established that a good

correlation exists between the 40J Cv energy transition temperature and the NDTT for older, less clean steels where the sulphur and carbon composition, expressed as 10S+C, was greater than 0.25%. However, the Cv energy at the NDTT was found to increase rapidly for modern clean steels as the sulphur and carbon content fell below 10S+C < 0.25%. Graville concluded that no useable correlations between Cv energy properties and the NDTT could be found for modern steels.

4.7. Other Correlations

The correlations which are summarised in this section include those for which it is not clear as to which regime of the temperature transition curve they apply.

Hartbower et al (77) have developed correlations between pre-cracked instrumented and slow-bend Charpy energies and fracture toughness, of the form (see Appendix A.7.1):

$$K_{Ic} = a \frac{Cv}{A} + b \qquad [30]$$

These correlations are applicable to certain titanium alloys, although Roberts and Newton (16), who have reviewed this correlation, do not state the specific material types.

Ronald et al (78) have developed a correlation which is applicable to steel and titanium alloys (see Appendix A.7.2):

$$K_{Ic}^2 = a \frac{E}{1 - \nu^2} \frac{Cv_{psb}}{A} \qquad [31]$$

where Cv_{psb} is the pre-cracked slow-bend Charpy energy.

Ito et al (79) have derived a correlation which is applicable to welded low alloy quenched and tempered steels, as well as 'plain alloy steels' (see Appendix A.7.3):

$$(K_{Ic})^2 = a \frac{Cv}{\sigma_y} \qquad [32]$$

The National Materials Advisory Board (70) have presented a correlation which is applicable to medium and high strength steels, in terms of pre-cracked slow-bend Charpy energies (see Appendix A.7.4):

$$\frac{K_{Ic}^2}{E} = a + b\,\frac{Cv_{psb}}{A} \qquad [33]$$

The load at fracture, P_f, of an instrumented Charpy impact test can be correlated with the dynamic fracture toughness:

$$K_{Id} = a\,P_f \qquad [34]$$

Nogata and Takahashi (80) have developed a correlation which is applicable to irradiated and non-irradiated nuclear pressure vessel steels, including weldments (see Appendix A.7.5):

$$K_{Ic} = a\left(\frac{Cv_{us}}{Cv} - 1\right)^{b} + c \qquad [35]$$

where Cv_{us} is the upper-shelf Charpy impact energy.

Yi et al (42) have developed correlations for two grades of medium strength steels (see Appendix A.7.6):

$$K_{Ic} = a\,\frac{Cv\ \sigma_y}{W\ \phi}\ \left(\frac{B}{B_o}\right) \qquad [36]$$

Where ϕ is a function of crack depth/width ratio. This correlation represents a lower-bound fit, and has been derived for side-grooved Charpy specimens.

Nageswara Rao and Acharya (44) have derived a dimensionally consistent correlation, valid for several non-standard Charpy specimen sizes. This correlation has been developed from data on a high strength steel, including weldments (see Appendix A.7.7):

$$\left(\frac{K_{Ic}}{\sigma_y}\right)^2 \left(\frac{\sigma_y}{Cv}\right)^{1/3} = a \qquad [37]$$

4.8. Correlations for Weldments

Several published correlations are based on material data which includes welds (21,30,31,52,67). The reader is referred to Appendix A where these correlations are discussed in more detail.

Other correlations are more specifically concerned with data obtained from welded joints (66,74,79,80). Again, the reader is referred to Appendix A for details.

Several correlations have been developed to give conservative, lower-bound estimates of fracture toughness for a wide range of materials, including weldments. These include the BSI PD6493:1991 Appendix B recommendations (1) and statistically-based temperature transition curve approximations (25-27,35). It is not clear whether other conservative procedures, such as those of the PVRC (29), NMAB (70) and ASME III (22), also include data from welded joints. The reader is referred to Appendix A for details.

Several authors have presented data which indicate correlations between Charpy test parameters and fracture toughness for material from welded joints, but have not derived correlations in an explicit form. Noteably, Dolby (81) and Verburg (82) provide extensive data for weldments of various materials for various welding conditions.

The database of CTOD and Charpy V toughness measured in weld metals of the type used in offshore construction originally published by Dolby (81), was subsequently enlarged with contributions from Pisarski (83) and Jones and Pisarski (84) to cover MMA, FCAW and SA weld metals. The work was detailed in the background document to the UK Department of Energy (DEn) guidance on structural steels in offshore structures (85). These correlations related the mean CTOD at -10°C in full thickness preferred geometry specimens (to BS5762) notched into weld metal, to the 40J transition temperature obtained from the weld root (the region generally having the lowest toughness), as illustrated in Fig.2. The earlier detailed work (84) suggested that weld metal yield strength had a marked effect on the Charpy V transition temperature, as illustrated in Fig.3. Some further data from postweld heat treated MMA, FCAW and SA weld deposits were included in the DEn background document (85). However, these correlations are suitable only for minimum design temperatures down to -10°C and not lower.

This restriction of minimum design temperature to -10°C, while entirely satisfactory for the UK continental shelf (UKCS), caused Braid (86) of CANMET to derive similar CTOD - Charpy V correlations for weld metals at temperatures down to -30°C, which were more suitable for Canadian east coast regions. Testing and analysis of MMA, FCAW and SA weld deposits was carried out to generate suitable

data for correlations. The resulting correlations between CTOD and 35J Charpy transition temperature supported the work of Dolby (81) and the subsequent UK DEn weld metal toughness requirements down to -10°C, however, the correlations for CTOD at -30°C indicated that in certain cases when using the DEn requirements extrapolated beyond their -20 to +10°C limits down to -30°C, some failures could be expected, as illustrated in Fig.4. Braid (89) has evaluated the following correlations:

$$\log \delta = 18.3 - 8.2 \log (T_t + 273) \quad \text{(mean fit, -30°C)}$$
$$\log \delta = 18.6 - 8.5 \log (T_t + 273) \quad \text{(lower bound, -30°C)}$$
$$\log \delta = 17.6 - 7.8 \log (T_t + 273) \quad \text{(mean fit, -10°C)}$$
$$\log \delta = 14.5 - 6.6 \log (T_t + 273) \quad \text{(lower bound, -10°C)} \qquad [38]$$

where T_t is the Charpy transition temperature.

The general rule by which the UK DEn and DnV specify the minimum Cv energy for offshore structures is to derive the minimum Cv energy in joules as a function of yield stress numerically equivalent to the yield stress in Nmm^{-2} divided by 10 (DEn: for $\sigma_y \leq 450 N/mm^2$) .

4.9. Correlations for High Strength Steels

There exist differences in perceived material strength grades between various branches of industry. For example shipbuilding and offshore jacket fabricators might consider a $500Nmm^{-2}$ yield stress material as being high strength, whilst the aerospace industry would place their definition of high strength material above, say, $800Nmm^{-2}$. Therefore, for the purposes of this section of the report, an arbitrary definition of high strength materials will be set at $500Nmm^{-2}$.

Amongst the correlations listed in Appendix A, there are a significant number which claim to cover ranges of material yield strength anywhere from $300Nmm^{-2}$ up to 900 or $1000Nmm^{-2}$ (20,21,28,32,67,68,75, 79). Some further correlations extend the upper range of applicability to $1400-1900Nmm^{-2}$ (24,69,70,76).

However, only one correlation specifically deals with high strength steels in the yield stress range $1600-1980Nmm^{-2}$ (Ault et al (74). This is an upper shelf correlation covering Charpy energies from 15 to 28.6J and requires σ_y and Cv as input data, and although similar in form to that of Barsom et al (17-19), is generally more conservative (16).

The main body of correlations which include high strength materials in their claimed ranges of applicability appear to cover lower-shelf, transition and upper-shelf regimes with some of them attempting to synthesise the entire transition curve. The use of these correlations for high strength materials can only be sanctioned following a vali-

dation exercise using independent data. Pisarski (15) notes that, for lower strength steels, most correlations are conservative but that the level of conservatism reduces for higher strength steels.

5. COMPARISON AND DISCUSSION OF CORRELATIONS

Roberts and Newton (16) have reviewed many of the pre-1980 correlations, and have evaluated their performance. They have shown that most of the correlations that are of the form $K_{Ic} = a\ Cv^n$ predict quite similar results for Charpy impact values in the range 7 to 68J. Inertial effects and machine noise introduce errors at energies less than 7J, and the influence of the upper-shelf is marked at Charpy energies greater than 68J i.e. the correlation is adversely affected outside its limits.

Roberts and Newton (16) show that the correlation of Barsom et al (17-19) is the most conservative in the range 7 to 19J, while the correlation of Sailors and Corten (20) is more conservative for higher impact energies (16).

Roberts and Newton (16) have derived a lower-bound correlation to a number of published correlations (16-20, 69-71):

$$K_{Ic} = 8.47\ Cv^{0.63} \qquad [MPa.m^{\frac{1}{2}},\ J]$$

$$= 9.35\ Cv^{0.63} \qquad [ksi.in^{\frac{1}{2}},\ ft.lb] \qquad [39]$$

This correlation is recommended (16) where a high degree of conservatism is required, such as in critical or unrefined analyses. A similar exercise was performed (16) with the upper-shelf correlations of Barsom et al (17-19) and Ault et al (73), and these results are given in Appendix A.5.2.

Roberts et al (16) have compared correlations with pre-cracked and instrumented impact Charpy results in the transition regime. However, these were not based on sufficient data for pressure vessel steels to evaluate their performance. Nevertheless, the correlations (17-19, 70,78) are reasonably close in the range of Charpy energies of 7 to 68J. The correlation of Barsom et al (17-19) is a lower-bound to those of NMAB (70) and Ronald et al (78).

The correlations between dynamic fracture toughness, K_{Id}, and Charpy energy, Cv, in the transition regime, which include those due to Marandet and Sanz (21), Barsom et al (17-19) and Sailors and Corten (20) show pronounced scatter in the Charpy energy range 7 to 68J. The correlation of Sailors et al is the most conservative in the range 12

to 68J, and similarly that of Barsom et al (17-19) is the most conservative in the range 7 to 12J. Roberts and Newton (16) have fitted a lower-bound correlation to the supporting data of these three correlations:

$$K_{Id} = 22.5\ Cv^{0.17} \qquad [MPa.m^{\frac{1}{2}},\ J]$$

$$= 21.6\ Cv^{0.17} \qquad [ksi.in^{\frac{1}{2}},\ ft.lb] \qquad [40]$$

This correlation represents a lower-bound confidence of 95% (obtained by lowering the best fit to the data by two standard deviations).

Roberts and Newton (16) have compared the correlations and temperature shifts of other authors (17-19, 21) with independent data for A533B steel obtained from Hawthorne et al (87). Insufficient data was available to evaluate the correlation of Iwadate et al (88) and Tetelman et al (67). They (16) have shown that the correlations which include a temperature shift in the transition regime, to account for strain-rate effects, predict the form of the K_{Ic} temperature transition curve more accurately than the single-step correlations such as those of Sailors and Corten (20) and Barsom et al (17-19).

Roberts and Newton (16) have investigated the dependence of correlations of the form $K_{Id} = a\ Cv^n$ on individual materials, using data from the literature. The effect of temperature-shift techniques, to account for strain-rate effects, were not considered, although the material dependence of K_{Ic} should be similar to that of K_{Id}. A range of materials, including SAE 1035, A36, A242, A440, A441, A514, A517, A572 and A588 were considered. An average of 15 data points were available for each material (minimum of five data points for A572 and a maximum of 33 for A588). Values of the constant 'a' ranged from 13.4 for A441 to 44.9 for A242. Values of the exponent 'n' ranged from 0.05 for A242 to 0.41 for A441, while for all of the data combined, n = 0.17 and a = 21.6. The units of Cv used in these calculations is ft.lb, and the units of K_{Id} are $ksi.in^{\frac{1}{2}}$. All of the results presented by Roberts et al represent a 95% confidence lower-bound, corresponding to lowering the best fit by two standard deviations.

Pisarski (15) has also compared many of the pre-1980 correlations, by collecting together data from the literature on steels with yield strengths in the range 270 to 813N/mm² for a range of temperatures.

Pisarski (15) observed that no single correlation describes completely the K_{Ic} transition curve obtained from these data, and warns that care must be taken in choosing a correlation which will best describe the material of interest. He has found that, for low strength steels, most of the published correlations are conservative, and this conservatism decreases for high strength steels.

Correlations based on dynamic K_{Id} toughness generally form lower-bounds to quasi-static K_{Ic} values (15). Some of the correlations based on referencing temperatures, such as T_{40J}, are not conservative throughout the transition regime. Pisarski has noted that there are few K_{Ic} data available to test the performance of the upper-shelf correlation.

From the discussion of Roberts and Newton (16) and Pisarski (15), it is clear that it is difficult to validate a large number of correlations which have been derived from data representing a large number of materials in such a fashion that the 'best' correlation can be chosen for a specific material.

The approach which has been adopted by Roberts and Newton (16) PD6493:1991 (1), ASME III, XI (2, 22) and the PVRC (29) is, essentially, to fit a lower-bound correlation to a very large set of material data, resulting in a conservative correlation. This approach has been adopted so as to produce a compact correlation which is easy to use, and conservative. This conservatism is necessary owing to the uncertainty associated with K_{Ic}-Cv correlations, and the scatter which occurs in both tests, caused by strain-rate effects, constraint, notch acuity and notch location, and variation in microstructure.

Statistically based correlations (25,27,35) provide techniques for evaluating fracture toughness from Charpy tests for a specific material in a more rational fashion, to known levels of confidence.

6. COMPUTER PROGRAM FOR K_{Ic} CORRELATIONS (CvK)

A PC based computer program (CvK) has been developed which implements suitable correlations which have been reviewed in this report. In total, 25 published correlations have been incorporated into CvK (see Table B.2 of Appendix B). This software also facilitates validation and comparison of the published correlations with independent data (TWI and user defined data). The program CvK is described in detail in Appendix B, which is intended as a user guide.

6.1. Program Structure

The program CvK is based around three graphical display modes where correlations and data may be displayed for comparison and use. The Primary Display mode permits the published correlations to be displayed, together with the data on which they are based (if available). TWI and user defined data may also be displayed for validation and comparison. The Log-linear Display mode displays the selected data on log-log axes, to which correlation equations are fitted by linear regression analysis. In the Comparison Display mode data sets may be compared in terms of each correlation, by plotting

actual toughness (K, CTOD or J) against predicted toughness (using the selected correlation equation).

In each display mode, the selected active correlation may be used to predict toughness (K, CTOD or J) from the relevant Charpy parameter (Cv, RT_{NDT}, etc). The correlation equation may be shifted to form a lower bound to the displayed data. Facilities are provided for printing a summary of the consultation (including correlation equation, graph, calculation results, information on the active correlation, and user defined text).

Material search facilities are provided so that relevant correlations can be selected for both specific and generic material selections. Generic material groups include low, medium and high strength steels, weldments, pressure vessel, pipeline, structural, ship and specialised steels and aluminium alloys. The specific materials are listed in CvK in the form presented in the literature (it has not been possible to determine equivalent ASTM or BS material grades for most specific materials).

The program interface is designed in terms of menus, which may be operated by mouse or keyboard. Help is available throughout the program in the form of text windows. The user may decide whether the program is to operate in SI or US unit systems. English or French language may be chosen. The text from Appendix A (detailed summaries of the published correlations) is included in the help option (English text only).

6.2. TWI Data

Six TWI data sets have been incorporated into the CvK program, based principally on data which have been generated during TWI project work (as well as (90)). The TWI data sets, which include data on parent plate and weldments, have been divided into 12 categories:

1. TWI-PV1(K): 9% Ni pressure vessel steel (A533I)
2. TWI-PV2(K): Nuclear pressure vessel steels (A508, A533B)
3. TWI-PV3(K): BS 1501 pressure vessel steels
4. TWI-PV4(K): A204 pressure vessel steel
5. TWI-PL(K): API 5L pipeline steels
6. TWI-ST(K): BS 4360 offshore structural steels
7. TWI-SH1(K): Lloyd's ship steel, high strain rate
8. TWI-SH2(K): Lloyd's ship steel, moderate strain rate
9. TWI-SH3(K): Lloyd's ship steel, standard strain rate
10. TWI-PP(δ): Parent plate, various steels
11. TWI-WM(δ): Weld metal, various steels
12. TWI-HAZ(δ): Heat affected zones, various steels

Details of these data sets may be found in the correlation information screens of CvK (see Appendix B), including weldments, consumables, thickness, Charpy energy and yield strength ranges and material grades. Clearly, there is a very large number of possible data sets which would be of interest, to resolve issues of material thickness, temperature, yield strength, etc for specific materials. It has not been possible to cover most of these effects. However, the 12 data sets which have been collected are sufficient to draw some general conclusions. The user data base facility of CvK enables other data sets of specific interest to the user to be displayed, compared, and applied.

Most of the toughness data which are measured at TWI are collected in terms of CTOD. The bulk of the correlations which have been reviewed in this report are presented in terms of K. To facilitate comparisons with these correlations, the TWI data which are in the form of δ_c values have been converted to K_c values using the expression (12):

$$\delta = K^2(1-\nu)^2/2E\sigma_y \qquad [41]$$

The above equation is not strictly valid, since δ_c values do contain a plastic component (small compared to δ_u or δ_m values). However, fracture assessment procedures such as BSI PD6493 (1) use the combined elastic and plastic components of fracture toughness. The value of K_c determined from [41] is not a lower bound toughness (K_{Ic}).

There is considerable scatter in some of the TWI data sets (see Table 1 for correlation coefficients). The data sets which have the lowest correlation coefficients (TWI-PV4(K) and TWI-SH3(K)) consist of only four data pairs. Most of the pressure vessel data sets, and the pipeline data set have reasonably high correlation coefficients (0.704 to 0.873).

6.3. Validation of Correlations

Owing to the scatter of the TWI data, and the varied requirements of potential users of CvK, it is not practicable to validate all correlations. It has been the intention, when developing CvK, that this software will provide an effective tool for the development, validation and application of correlations which are of specific interest to the user.

Of particular concern to the engineer who wishes to apply the published correlations, is how the correlation data and TWI data compare to the 'lower-bound' correlations, such as those presented in PD6493 (1), ASME (22) and PVRC (29). The upper-shelf correlation of

PD6493 (see Appendix A.6.5) generally forms a lower bound for Cv>25J, compared to other suitable published correlation data (except for some TWI data from 9% Ni A533 and offshore structural steel weldments, and for the data of Barsom et al (28) (see Fig.5 and 6)).

The cluster of five A533 data points in the range 40≤ Cv ≤ 66J, 37 ≤ K_c ≤ 71MPa√m, which fall below the PD6493 correlation line (Fig.6) include parent plate, weld metal and HAZ data. The eight data points from BS4360 offshore structural steels which lie below the PD6493 correlation line, relate principally to HAZ testing, and include pop-ins (one weld metal data point also lies in this region). Most data from pressure vessel steels (except A553) lie significantly above the PD6493 correlation line.

The data sets TWI-PP(δ), TWI-WM(δ) and TWI-HAZ(δ), which are based on CTOD (including δ_c, δ_u and δ_m values), relate to parent material, weld metal and HAZ respectively. Effects such as thickness, yield strength, temperature and specific material have not been considered. Correlation coefficients for the parent plate, weld metal and HAZ data sets are 0.570, 0.316 and 0.423, respectively (see Fig.7).

Thus, Fig.6 would suggest that 'lower-bound' correlations such as PD6493 are not safe to use for HAZs (for offshore structural steels). There are inherent uncertainties associated with Cv-K correlations of HAZ regions, as discussed in Section 2.1. However, the CTOD-based TWI data sets (which are fairly coarse) do not confirm this, with the weld metal data set having the lowest correlation coefficient. It may be that these issues can only be satisfactorily resolved if a significantly greater number of data sets are collected, relating to specific materials, temperatures, thicknesses, etc.

For Charpy energies in the range Cv < 25J, many data points lie below the PD6394 line (Fig.5). For Cv < 25J one might expect the lower-shelf/transition PD6493 correlation to predict lower values of K_{Ic}. However, this is difficult to confirm. the only correlations which can be compared directly to the lower-shelf/transition PD6493 correlation are those of the ASME/PVRC and Matsumoto et al (see Appendix A.2.2, A.2.4 and A.2.5). However, these three correlations are expressed in terms of different temperature transition reference parameters, and so can only be approximately compared. On this basis, the PD6493 and ASME correlations appear to be lower bounds. In addition, the absolute lower bound toughness predicted by the lower-shelf PD6493 correlation is K_{Ic} = 30MPa√m. No TWI data fall below this value.

7. SUMMARY AND CONCLUDING REMARKS

A critical review of published correlations between fracture toughness and Charpy impact energy has been carried out. In addition,

a PC based computer program (CvK) has been developed which permits suitable published correlations to be applied effectively. TWI and user defined data may be displayed together with the correlations, permitting correlations to be compared and validated, and their ranges of applicability extended:

1) A total of 31 published correlations have been reviewed and these have been summarised individually in Appendix A.

2) There are two significant review publications, (Pisarski (15) and Roberts and Newton (16) that between them cover the bulk of the pre-1980 correlations.

3) Several correlations include high yield stress materials in their upper range of applicability but only one (Ault et al (73)) specifically caters for correlations in such materials on their upper shelves (see Section 4.9).

4) Many of the published correlations (see Section 4.8) include data on weldments.

5) In total, 25 of the published correlations reviewed in this report have been incorporated into the correlation software CvK.

6) Twelve TWI data sets have been incorporated into CvK, grouped into the categories of pressure vessel, pipeline, ship and offshore structural steels (parent plate, weld metal and HAZ).

7) The codified correlations, such as PD6493 (1), ASME (22), and PVRC (29) appear generally to be conservative. In particular, the upper-shelf correlation of PD6493 is conservative for Charpy energies Cv > 25J, except for A553 9% Ni steel, and BS4360 offshore structural steel HAZs.

8) Insufficient data is available to verify the conservatism of the lower-shelf and transition correlations of PD6493, ASME and PVRC, which are based on Charpy transition reference temperatures. The absolute lower bound toughness predicted by PD6493, ASME and PVRC (K_{Ic} = 30MPa√m) has been shown to be conservative.

8. ACKNOWLEDGEMENTS

The authors wish to acknowledge the assistance of H G Pisarski, S J Garwood, C S Wiesner, E Moreau and S Tesai of the Engineering Department at TWI, as well as the project Working Group: A G Glover (chairman), J M Frund, M C Smith, A Clyne and R T J Whillock. This work has been funded by the organisations listed in Table 2.

9. REFERENCES

1 BSI PD6493:1991: 'Guidance on methods for assessing the acceptability of flaws in fusion welded structures', British Standards Institution, London.

2 ASME Boiler and Pressure Vessel Code. Section XI - Rules for in-service inspection of nuclear power plant components. Division 1, 1977, Ed. Cited by Pisarski H G: 1978, The Welding Institute Research Bulletin, 19, (12), 362-367.

3 Broek D: 1982, 'Elementary engineering fracture mechanics', Martinus Noordhoff, The Hague.

4 Ewalds H L, Wanhill R J H: 1984, 'Fracture mechanics', Edward Arnold/Delftse Uitgevers Maatschappij, Delft, The Netherlands.

5 CP/ENG/4986-1: Critical examination of Charpy V fracture toughness correlations, TWI, 1980.

6 Phaal R, Macdonald K A: 'Critical examination of correlations between fracture toughness and Charpy impact energy', TWI Report 5605/3/91, 1991.

7 Phaal R, Macdonald K A: 'Critical examination of correlations between fracture toughness and Charpy impact energy. Appendix A: Correlation summaries', TWI Report 6505/3A/91, 1991.

8 BS EN 10045-1: 'Metallic materials - Charpy impact test - Part 1: Test method', European Committee for Standardisation, Brussels, 1990.

9 ASTM E23:1988, 'Standard test methods for notched bar impact testing of metallic materials'.

10 BS 5447:1977, 'Method of test for plane-strain fracture toughness (K_{Ic}) of metallic materials'.

11 ASTM E399:1983, 'Test method for plane-strain fracture toughness of metallic materials'.

12 BS 7448 Part 1: 'Method for determination of K_{Ic}, critical CTOD and critical J values of metallic materials', British standards Institute, London, 1991.

13 ASTM E1290-89: 'Test method for crack-tip opening displacement (CTOD) fracture toughness measurement'.

Copyright © TWI 1992

14 ASTM E813-89: 'Test method for J_{Ic}, a measure of fracture toughness'.

15 Pisarski H G: 1978, 'A review of correlations relating Charpy energy to K_{Ic}', The Welding Institute Research Bulletin, 19, (12), 362-367.

16 Roberts R, Newton C: 1981, 'Interpretive Report on small-scale test correlations with K_{Ic} data'. Welding Research Council Bulletin, 265, 1-18.

17 Barsom J M, Rolfe S T: 1970. 'Correlations between K_{Ic} and Charpy V notch test results in the transition temperature range', ASTM-STP-466, 281-302. Cited by Pisarski H G: 1978, The Welding Institute Research Bulletin, 19, (12), 362-367.

18 Rolfe S T, Novak S T: 1970, 'Slow bend K_{Ic} testing of medium strength high toughness steels', ASTM-STP-463, 124-159. Cited by Pisarski H G: 1978, The Welding Institute Research Bulletin, 19, (12), 362-367.

19 Rolfe S T, Barsom J M: 1977, 'Fracture and fatigue control in structures - application of fracture mechanics', Prentice-Hall. Cited by Roberts et al: 1981, Welding Council Research Bulletin, 265, 1-18.

20 Sailors R H, Corten H T: 1973, 'Relationship between material fracture toughness using fracture mechanics and transition temperature tests', ASTM-STP-514, 164-191. Cited by Pisarski H G: 1978, The Welding Institute Research Bulletin, 19, (12), 362-367.

21 Marandet B, Sanz G: 1977, 'Evaluation of the toughness of thick medium strength steels by LEFM and correlations between K_{Ic} and CVN', ASTM-STP-631, 72-95. Cited by Pisarski H G: 1978, The Welding Institute Research Bulletin, 19, (12), 362-367.

22 ASME Boiler and Pressure Vessel Code, 'Section III - Rules for construction of nuclear power plant components', 1989, 572-577.

23 Ritchie R: 1978, 'On the relationship between fracture toughness and Charpy V notch energy in ultra high strength steel', What does the Charpy test really tell us?, Proc Symp American Inst Mining Metallurgical and Petroleum Engineers, Denver, Colorado, February 27-28 1978, American Society for Metals.

24 Norris D M, Reaugh J E, Server W L: 1981, 'A fracture-toughness correlation based on Charpy initiation energy', Fracture Mechanics: 13th Conference, ASTM-STP-743, Ed: Roberts R, American Society for Testing and Materials, 207-217.

Copyright © TWI 1992

25 Oldfield W, Server, W L: 1984, 'Fracture toughness prediction for pressure vessel steels: the development of a statistically based method', Reference fracture toughness procedures applied to pressure vessel materials, Ed: Mager T R: Presented at the Winter annual meeting of the American Society of Mechanical Engineers, New Orleans, Louisiana, December 9-14 1984, 9-26.

26 Oldfield W: 1980, 'Development of fracture toughness reference curves', J of Eng Mat and Tech, 102, (1), 107-117.

27 Wullaert R A, Oldfield W, Server W L: 1980, 'Reference fracture toughness curves for irradiated pressure vessel steels', J of Eng Mat and Tech, 102, (1), 101-106.

28 Barsom J M: 1975, 'Development of the AASHTO fracture mechanics requirements for bridge steels', Engineering Fracture Mechanics, 7, 605-618. Cited by Roberts et al: 1981, Welding Research Council Bulletin, 265, 1-18.

29 PVRC: 1972, 'Recommendations on toughness requirements for ferritic materials', Welding Research Council Bulletin, 175, August. Cited by Pisarski H G: 1978, The Welding Institute Research Bulletin, 19, (12), 362-367.

30 Matsumoto K, Takai K, Matsumura K, Ogushi T, Hamada K: 1978, 'Effect of post-weld heat treatment on fracture mechanics properties of electroslag-welded joints of low carbon steel plates', 3rd Int Symp of Japan Welding Soc: Criteria for preventing service failures in welded structures, 26-28 Sep 1978, Tokyo, JWS, 167-172.

31 Kanazawa T, Machida S, Miyata T: 1974, 'Present status on the evaluation criteria of fracture toughness for structural steels and their welded joints in Japan', Proc of an Int Conf on Prospects of Fracture Mechanics, Ed: Sih G C, van Elst H C, Broek D, Delft University of Technology, The Netherlands, June 24-28, 1974, 547-561.

32 Oda I: 1988, 'Inference of critical COD from Charpy V test result', Eng Frac Mech, 29, (6), 663-671.

33 Irwin G R, Kraft J M, Paris P C, Wells A A: 1967, 'Basic aspects of crack growth and fracture', Naval Research Laboratory Report 6598, Nov 21. Cited by Roberts et al: 1981, Welding Research Bulletin, 265, 1-18.

34 Pellini W S: 1968, 'Advances in fracture toughness characterisation procedures and in quantitative interpretations to fracture safe design for structural steels', Naval Research Laboratory Report No. 6713. Cited by Roberts et al, 1981, Welding Council Research Bulletin, 215, 1-18.

Copyright © TWI 1992

35 Richardson A K, Server W L, Reuter W G: 1985, 'Adequacy of estimates and variability of fracture-related properties for reactor vessel materials', Int J Pres Ves & Piping, 19, 299-315.

36 ASTM E208-87a: 'Method for conducting drop weight test to determine nil ductility transition temperature of ferritic steels'.

37 Yukawa S, Merkle J G: 1984, 'Development of the present reference fracture toughness curves in the ASME nuclear code', Reference fracture toughness procedures applied to pressure vessel materials, Ed: Mager T R: Presented at the Winter annual meeting of the American Society of Mechanical Engineers, New Orleans, Louisiana, December 9-14 1984, 1-7.

38 Willoughby A A: 1979, 'Discussion: "A simple test method for measuring 'valid' J_{Ic} fracture toughness in Charpy-size surveillance specimens of nuclear pressure vessel steel", Int J Frac, 15, R125-R126.

39 Ritchie R D, Server W L, Wullaert R A: 1979, 'Response: discussion of "a simple test method for measuring 'valid' J_{Ic} fracture toughness in Charpy-size surveillance specimens of nuclear pressure vessel steel" by A A Willoughby', Int J Frac, 15, R139-R141.

40 Neale B K: 1983, 'The determination of J_q, the initiation elastic-plastic toughness parameter, using pre-cracked Charpy specimens', Int J Pres Ves & Piping, 12, 207-227.

41 Pati S R: 1986, 'Fracture toughness determination from side-grooved pre-cracked Charpy specimens', The mechanism of fracture: Int Conf and Exposition on fatigue, corrosion cracking, fracture mechanisms and failure analysis, Ed: Goel V S, 2-6 December 1985, Salt Lake City, USA, American Society for Testing and Materials, 487-493.

42 Yi L, Xue-Wen T, Nai-Ji L, Xiao-Wei L: 1987, 'Determination of K_{IC} of mild steel by the impact method of testing side-grooved pre-cracked TPB specimens', Eng Frac Mech, 28, (3), 361-364.

43 Yi L, Xiao-Wei L: 1988, 'A simple test method for determining J_{Ic} of mild steel by means of single side-grooved pre-cracked Charpy-type specimens', Eng Frac Mech, 31 (3), 381-384.

44 Nageswara Rao B, Acharya A R: 1989, 'Charpy V-notch impact test: a partial alternative to ASTM E399 fracture testing for routine quality control applications', Eng Frac Mech, 32, (1), 39-42.

45 Anil Kumar P V, Nageswara Rao B, Acharya A R: 1990, 'Statistical scatter in fracture toughness of M250 grade maraging steel predicted from Charpy V notch impact test, Eng Frac Mech, 37 (4), 735-738.

Copyright © TWI 1992

46 Neale B K, Priest R H: 1985, 'The unloading compliance method for crack length measurement using compact tension and pre-cracked Charpy specimens', Elastic-plastic fracture test methods: the user's experience, ASTM-STP-856, Ed: Wessel E T, Loss F J, American Society for Testing and Materials, Philadelphia, 375-393.

47 Kapp J A: 1985, 'J-R curve determination using pre-cracked Charpy specimens and the load-drop method for crack growth measurements', Fracture Mechanics: Sixteenth Symp, ASTM-STP-868, Ed: Kanninen M F, Hopper A T, American Society for Testing and Materials, Philadelphia, 281-292.

48 Kapp J A, Jolles M I: 1986, 'Assessment of J-R curves obtained from pre-cracked Charpy specimens', Fracture Mechanics: Seventeenth Volume, ASTM-STP-905, Ed: Underwood J H, Chait R, Smith C W, Wilhem D P, Andrews W A, Newman J C, American Society for Testing and Materials, Philadelphia, 401-411.

49 Succop G, Bubsey R T, Jones M H, Brown Jr. W F: 1977, 'Investigation of some problems in developing standards for pre-cracked Charpy slow bend tests', Developments in fracture mechanics test methods standardization, ASTM-STP-632, Ed: Brown Jr. W F, Kaufman J G, American Society for Testing and Materials, Philadelphia, 153-178.

50 Succop G, Brown Jr, W F: 1977, 'Estimation of K_{Ic} from slow bend pre-cracked Charpy specimen strength ratios', Developments in fracture mechanics test methods standardization, ASTM-STP-632, Ed: Brown Jr. W F, Kaufman J G, American Society for Testing and Materials, Philadelphia, 179-192.

51 Tanner G M, Bradley W L: 1988, 'Evaluation of the fracture toughness of ductile iron using fatigue pre-cracked Charpy, dynamic tear, and compact tension specimens', Fracture Mechanics, Eighteenth Symposium, ASTM-STP-945, Ed. Read D T, Read R P, American Society for Testing and Materials, Philadelphia, 405-418.

52 Witt F J: 1983, 'Relationships between Charpy impact-shelf energies and upper-shelf K_{Ic} values for reactor pressure vessel steels', Int J Pres Ves & Piping, 11, 47-63.

53 Robinson J N, Tetelman A S: 1976, 'Comparison of various methods of measuring K_{Ic} on small pre-cracked bend specimens that fracture after general yield', Eng Frac Mech, 8, 301-313.

54 Ruiz C, Mines R A W: 1985, 'The Hopkinson pressure bar: an alternative to the instrumented pendulum for Charpy test', Int J Frac, 29 101-109.

55 Kobayashi T: 1984, 'Analysis of impact properties of A533 steel for nuclear reactor pressure vessels by instrumented Charpy test', Eng Frac Mech, 19 (1), 49-65.

56 Kobayashi T: 1984, 'On the information about fracture characteristics obtained from instrumented impact tests of A533 for nuclear reactor pressure vessels', Eng Frac Mech, 19 (1), 67-79.

57 Kobayashi T, Yamamoto I, Niinomi M: 1986, 'Evaluation of dynamic fracture toughness parameters by instrumented Charpy impact test', Eng Frac Mech, 24 (5), 776-782.

58 Kobayashi T, Yamamoto I, Niinomi M: 1987, 'On the accuracy of measurement of dynamic elastic-plastic fracture toughness parameters by the instrumented Charpy test', Eng Frac Mech, 26 (1), 83-94.

59 Kobayashi T: 1983, 'Measurement of dynamic fracture toughness J_{Id} by instrumented Charpy test', Int J Frac, 23 E105-R109.

60 Kishimoto K, Aoki S, Sakata M: 1980, 'Simple formula for dynamic stress intensity factor of pre-cracked Charpy specimen', Eng Frac Mech, 13, 501-508.

61 Johnson F A, Glover A P, Radon J C: 1976, 'Fracture toughness and fracture energy measurements on aluminium alloys', Eng Frac Mech, 8, 381-390.

62 Martin E, Macke T, Quenisset J M: 1986, 'Fracture parameters determination at yield point and fracture initiation in instrumented impact testing', Eng Frac Mech, 24 (6), 821-836.

63 Kucer J, Talpa I, Smid V; 1980, 'On the fracture of laminated Charpy V notch specimens', Proc Int Conf on Analytical and Experimental Fracture Mechanics, 23-27 June, Rome, Sijthoff und Noordhoff, The Netherlands, 515-525.

64 Graville B A: 1988, 'Correlations between Charpy properties and the nil-ductility transition temperature', Project 1-1, CSA verification program for the Offshore Structures Code, Graville Associates Inc.

65 Hertzberg R W: 1983, 'Deformation and fracture mechanics of engineering materials', 2nd Ed., John Wiley and Sons, New York.

66 Chaudhuri S K, Ojha S N, Ramaswamy V: 1986, 'Fracture toughness evaluation of weldments and correlations with the Charpy data of a micro-alloyed steel', Int J Pres Ves & Piping, 22, 23-30.

Copyright © TWI 1992

67 Tetelman A S, Wullaert R A, Ireland D: 1971, 'Prediction of variation in fracture toughness from small specimen tests', Practical Applications of Fracture Mechanics to Pressure Vessel Technology, Institution of Mechanical Engineers, 85-92. Cited by Roberts R, Newton C: 1981, Welding Research Council Bulletin, 265, 1-18.

68 Imai J, Nakaya I, Yajima H, Tada M, Yamagata S, Deguchi A: 1984, 'Safety evaluation of LNG storage tanks of 9% Ni steel based on fracture analysis', Proc: Transport and storage of LPG and LNG, 1, Brugge 7-10 May 1984, 91-100.

69 Logan J G, Crossland B: 1971, 'The fracture toughness of (En25) and a 3%Ni-Cr-Mo-V steel at various strength levels together with Charpy impact data', Practical Applications of Fracture Mechanics to Pressure Vessel Technology, Institution of Mechanical Engineers, 148-155. Cited by Roberts et al: 1981, Welding Research Council Bulletin, 265, 1-18.

70 National Materials Advisory Board: 1976, 'Rapid inexpensive tests for determining fracture toughness', Report No. NMAB-328, National Academy of Sciences. Cited by Roberts et al: 1981, Welding Research Council Bulletin, 265, 1-18.

71 Thorby P N, Ferguson W G: 1976, 'The fracture toughness of HY60', Materials Science and Engineering, 22, 177-184. Cited by Roberts et al: 1981, Welding Research Council Bulletin, 265, 1-18.

72 Shoemaker A K, Rolfe S T: 1971, 'The static and dynamic low-temperature crack-toughness performance of seven structural steels', Engineering Fracture Mechanics, 2, 87-93. Cited by Roberts et al, 1981, Welding Council Research Bulletin, 265, 1-18.

73 Ault R T, Wald G M, Bertolo R B: 1971, 'Development of an improved ultra-high strength steel for forged aircraft components', AFML-TR-71-27, Air Force Materials Laboratory. Cited by Roberts et al: 1981, Welding Research Council Bulletin, 265, 1-18.

74 Priest A H, Charnock W, Stewart A T: 1982, 'The effect of accelerated irradiation on fracture behaviour', Effects of radiation on materials: 11th conference, ASTM-STP-782, Ed: Brager H R, Perrin J S, American Society for Testing and Materials, 475-491.

75 Begley J A, Logsdon W A: 1971, 'Correlation of fracture toughness and Charpy properties for rotor steels', Westinghouse Research Laboratories Scientific paper 71-1E7-MSLRF-P1, presented at the 5th Nat. Symp. on Fracture Mechanics, Pittsburg, P Cited by Pisarski H G: 1978, The Welding Institute Research Bulletin, 19, (12), 1978, 362-367, and by Roberts et al: 1981, Welding Research Council Bulletin, 265, 1-18.

Copyright © TWI 1992

76 Girenko V S, Lyndin V P: 1985, 'Relationship between the impact strength and fracture mechanics criteria δ_{Ic} and K_{Ic} of structural steels and welded joints in them', Automatic Welding, September, 13-19.

77 Hartbower C E, Reuter W G, Crimmens P O: 1969, 'Tensile properties and fracture toughness of 6Al-4V titanium', AFML-68-163, Air Force Materials Laboratory, Dayton, OH. Cited by Roberts R, Newton C: 1981, Welding Research Council Bulletin, 265, 1-18.

78 Ronald T M F, Hall J A, Pierce C M: 1972, 'Usefulness of pre-cracked Charpy specimens for fracture toughness screening tests of titanium alloys', Metallurgical Transactions, 3, 813-818. Cited by Roberts et al: 1981, Welding Research Council Bulletin, 265, 1-18.

79 Ito T, Tanaka K, Sato M: 1973, 'Study of brittle fracture initiation from surface notch in welded fusion line'. IIW Doc. No. X-704-73. Cited by Pisarski H G, 1978, The Welding Institute Research Bulletin, 19, (12), 362-367.

80 Nogata F, Takahashi H, 1986: 'Fracture mechanics evaluation of irradiated embrittlement in reactor vessel steels based on the rate process concept', J of Testing and Evaluation, JTEVA, 14, (1), 40-48.

81 Dolby R E: 1981, 'Charpy V and COD - correlations between test data for ferritic weld metals', Metal Construction, January, 43-51.

82 Verburg S J: 1980, 'Correlations between COD and impact test results of MMA weld metal in heavy butt joints', Philips Welding Reporter, 1980/3 & 1981/1, 40-44.

83 Pisarski H G: 1981,'Design for fracture avoidance in offshore structures', Int Conf Steel in Marine Structures, Paris, France, October.

84 Jones R L and Pisarski H G: 1984, 'A study of the mechanical properties of flux-cored wire welds in C-Mn steels', The Welding Institute Research Report, 241/1984, June.

85 Department of Energy: 1986, 'Background to new guidance on structural steel and steel construction standards in offshore structures', HMSO, London.

86 Braid J E M: 1987, 'Weld metal Charpy-CTOD correlations for cold marine applications', IIW Doc. No. X-1139-87, June.

Copyright © TWI 1992

87 Hawthorn J R, Mager T R: 1972, 'Relationship between Charpy V and fracture mechanics K_{Ic} assessments of A533B Class 2 pressure vessel steel', Fracture Toughness, Proc of the 1971 Nat Symp on Fracture Mechanics, Part II, ASTM-STP-514, 148-155. Cited by Roberts el al: 1981, Welding Research Council Bulletin, 265, 1-18.

88 Iwaldata T, Karaushi T and Watanabe J: 'Prediction of fracture toughness K_{Ic} of 2¼ Cr-1 Mo pressure vessel steels from Charpy V notch test results', Flaw growth and fracture, ASTM STP 631, 493-506. Cited by Roberts et al: 1981, Welding Research Council Bulletin, 255, 1-18.

89 Tyson W R: Personal correspondence, June 1991.

90 Wittenbach P: Personal correspondence, April 1991

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Table 1 Correlation coefficients for TWI data sets

Data set	Correlation coefficient, r
TWI-PV1(K)	0.836
TWI-PV2(K)	0.873
TWI-PV3(K)	0.704
TWI-PV4(K)	0.260
TWI-PL(K)	0.819
TWI-ST(K)	0.561
TWI-SH1(K)	0.865
TWI-SH2(K)	0.921
TWI-SH3(K)	0.066
TWI-PP(δ)	0.570
TWI-WM(δ)	0.316
TWI-HAZ(δ)	0.423

Correlation coefficient for combined set of K-based correlations: 0.523

Correlation coefficient for combined set of δ - based correlations: 0.443

Table 2 Sponsors of project 5605

Nuclear Electric plc
British Gas plc
Lloyds Register of Shipping
Powergen plc
Chevron UK Ltd
Nova Corporation of Alberta
Mobil North Sea Ltd
British Steel plc
Statoil
Supply & Services Canada
Health & Safety Executive
Phillips Petroleum Co Norway
ICI plc
Electricite de France
Department of Energy
ELF UK plc
Far East Levingston Shipbuild
American Bureau of Shipping

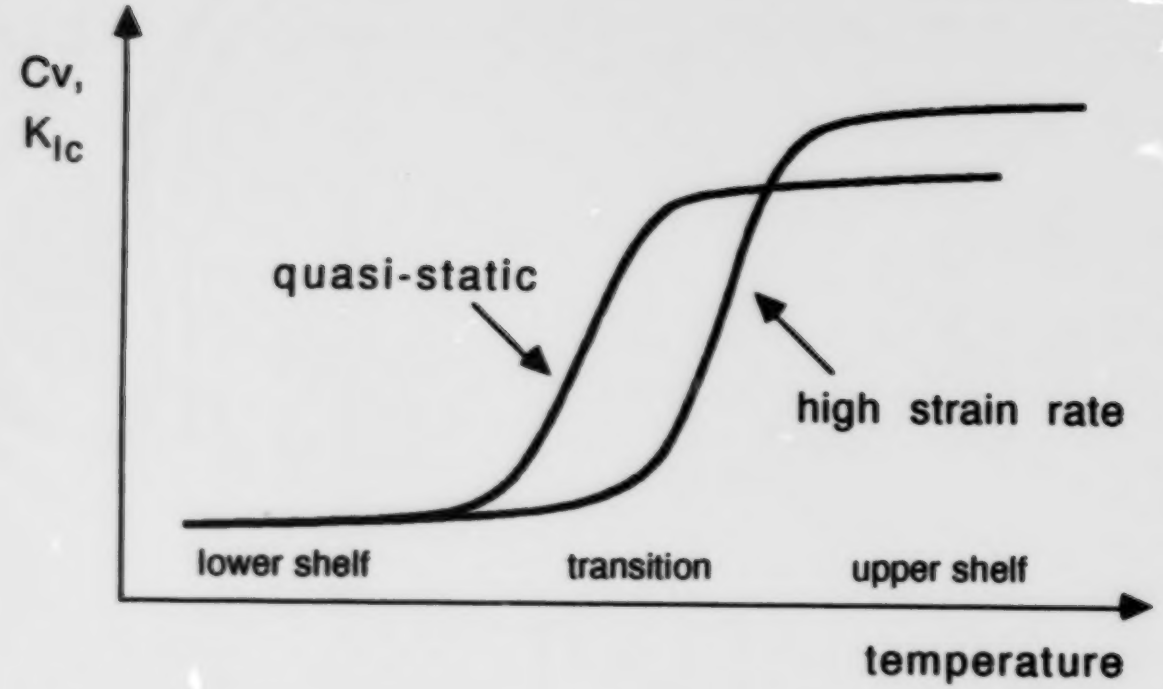

Fig 1. Temperature shift between Charpy and fracture toughness transition curves.

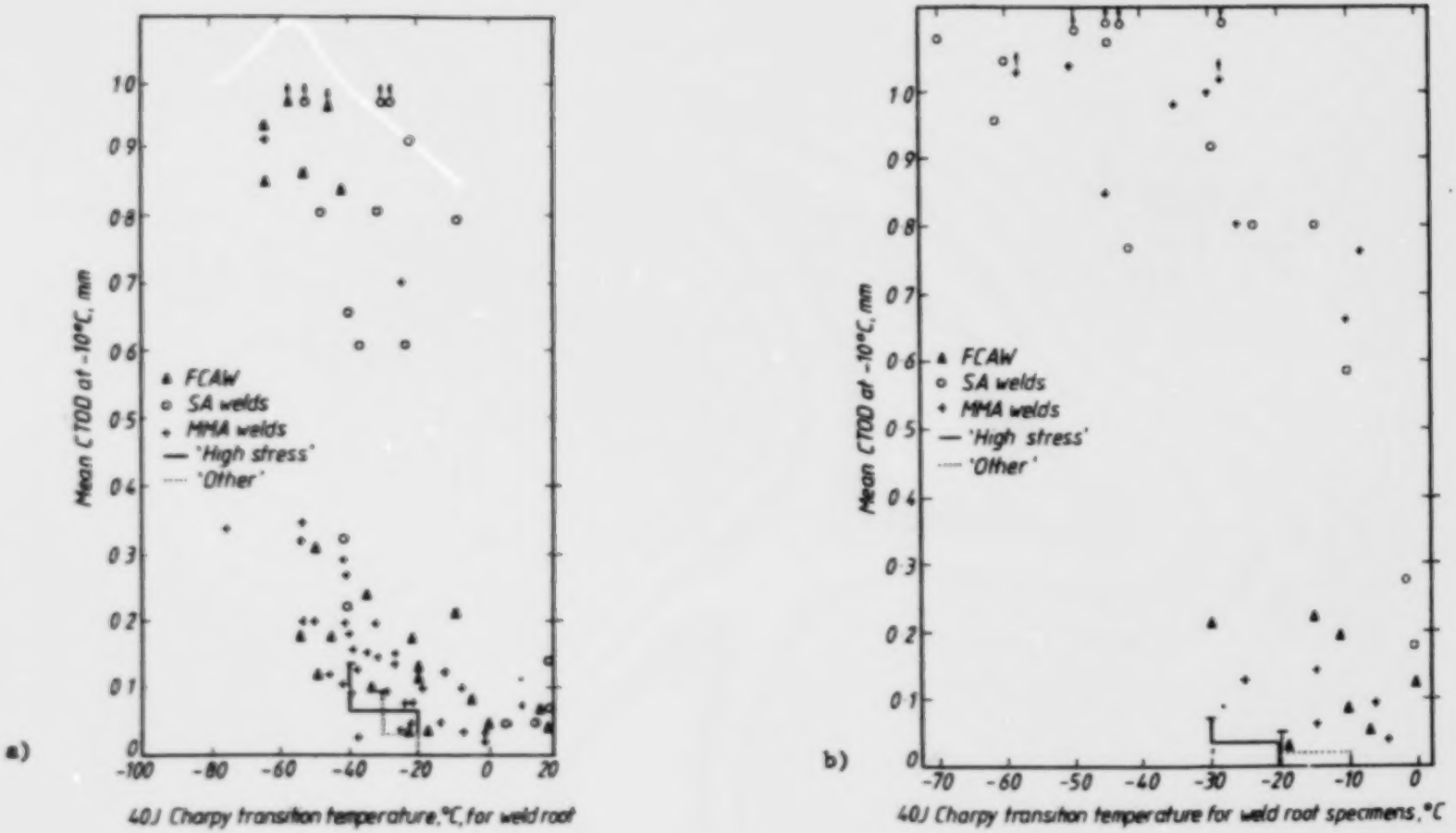

Fig 2. Correlation between mean CTOD at -10 deg C and the 40J transition temperature (Ref 85) for a) as-welded weld deposits b) postweld heat treated weld deposits

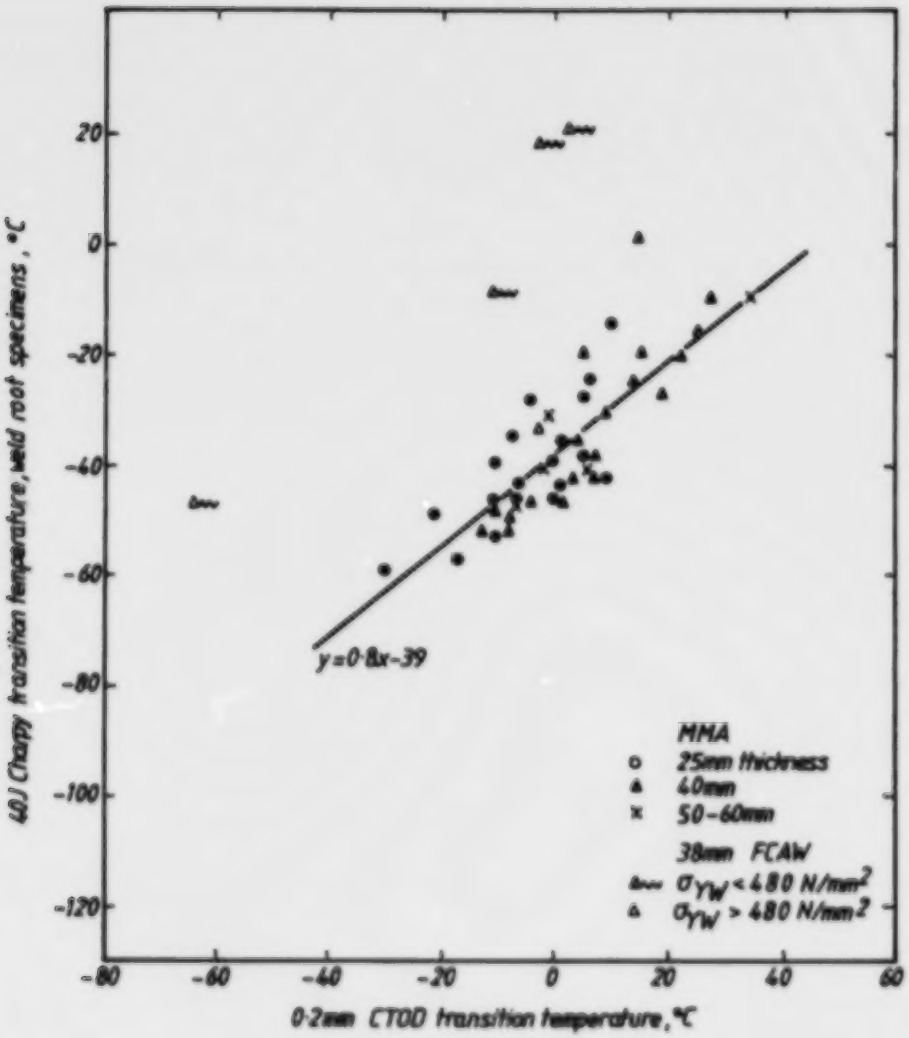

Fig 3 Correlation between the 40J Charpy and the 0.2mm CTOD transition temperatures for as-welded MMA multipass deposits (yield stresses 470–610 N/mm^2) (Ref 84).

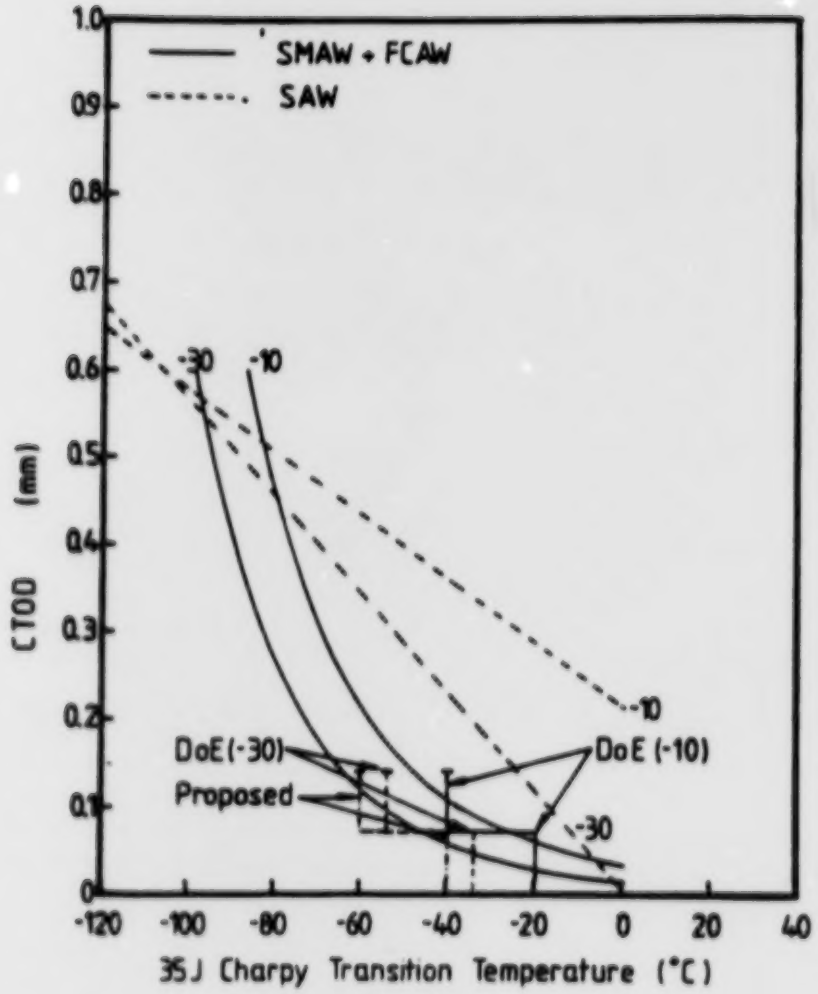

Fig 4 Summary of CTOD - 35J Charpy transition temperature results (Ref 8
showing the shift in 35J Charpy transition temperature due to a decrease i
CTOD test temperature from -10 to -30 deg C.

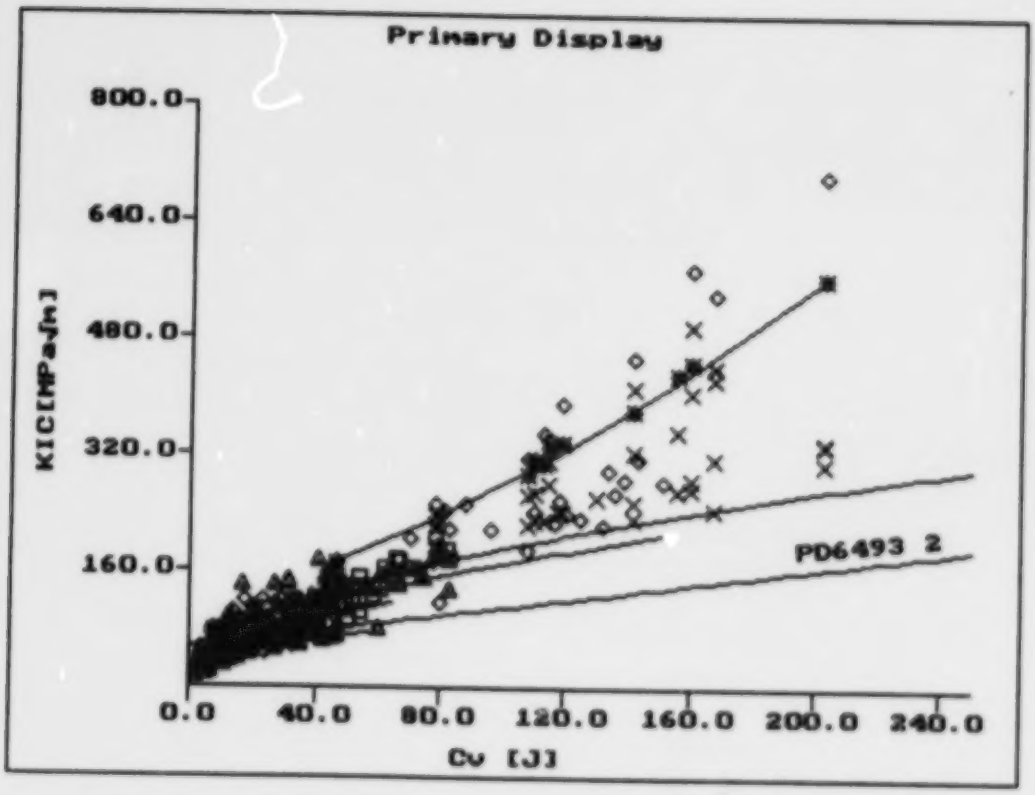

Fig.5 Published K_{Ic}-Cv correlations

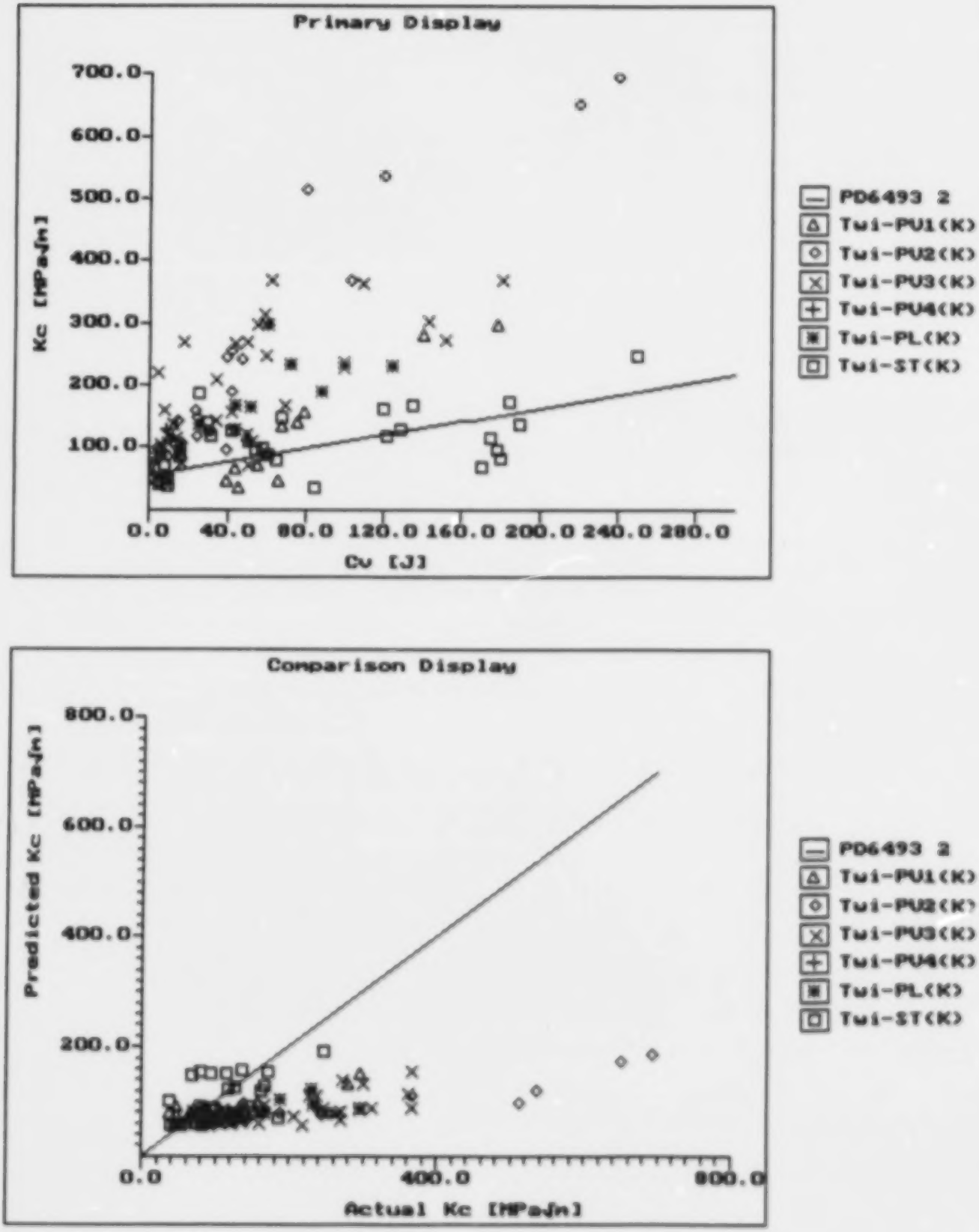

Fig.6 TWI data compared to PD6493 correlation

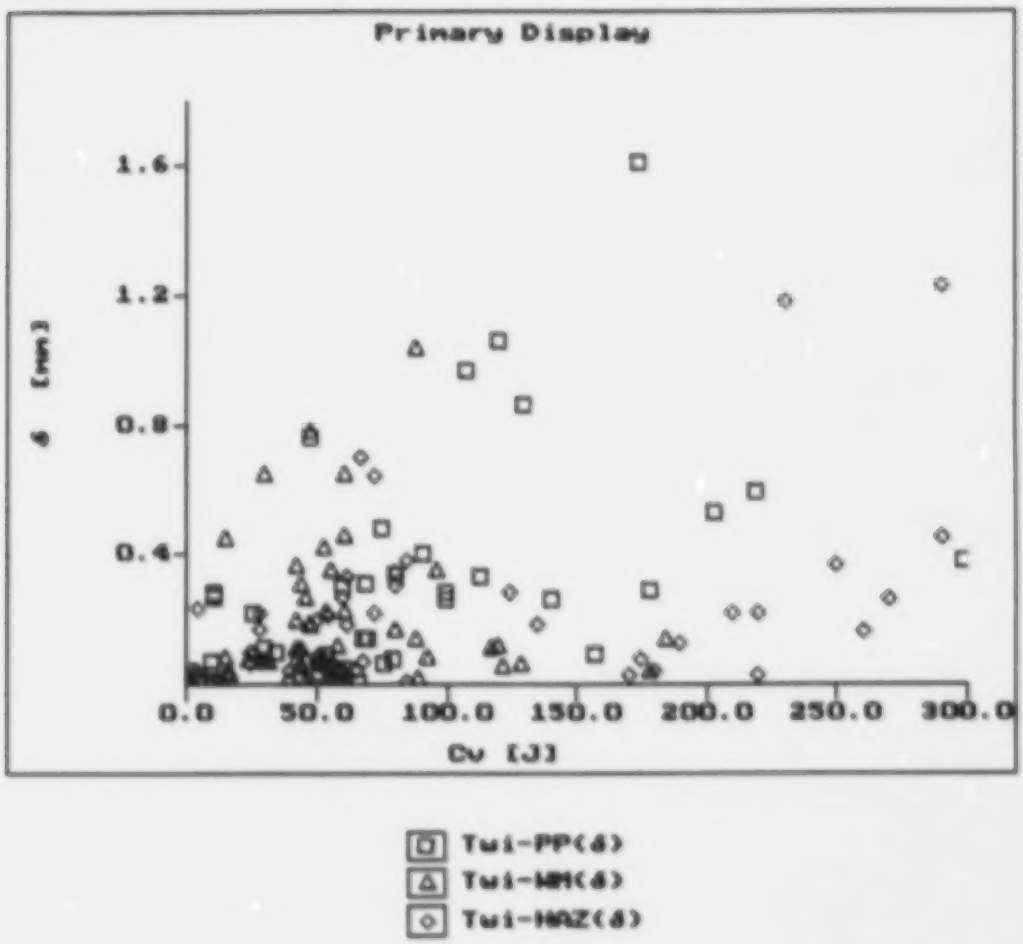

Fig.7 TWI-PP(δ), TWI-WM(δ) and TWI-HAZ(δ) data

APPENDIX A

Correlation summaries

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APPENDIX A: CORRELATION SUMMARIES

The correlations which have been reviewed for this report have been presented in their general form in the main body of the report. Each of these correlations is briefly summarised in this appendix, giving the equations in detail, in the form that they have been presented in the literature. Also, where possible, the materials, ranges of yield strength, Charpy energies and temperatures for which the correlations apply are presented.

The correlations have been separated broadly according to which temperature transition curve regime they apply:

A.1) Lower-shelf correlations.
A.2) Lower-shelf/transition correlations.
A.3) Transition correlations.
A.4) Transition/upper-shelf correlations.
A.5) Upper-shelf correlations.
A.6) Lower-shelf/transition/upper-shelf correlations.
A.7) Other correlations.

It should be noted that the division of the temperature transition curve into the lower-shelf, transition and upper-shelf regimes is not precise. In this report this classification is made according to the claims of the original paper or review.

Section A.7 summarises those correlations for which it is unclear as to which temperature transition curve regime they apply. Within each section the correlations are presented in chronological order.

A.1 LOWER-SHELF CORRELATIONS

A.1.1 Chaudhuri, Ojha and Ramaswamy (1986) (A1)

Chaudhuri et al have developed δ_c-Cv correlations which are applicable to weldments of 10mm thick APIX52 pipeline steel (σ_y = 530N/mm², σ_u = 660N/mm²) over a temperature range of -60°C to 0°C with Charpy impact energies of 18 to 64J. Submerged arc welds were examined which were made with Lincoln 761 flux, with a heat input rate of 1kJ/mm.

The following correlations are given for the HAZ:

$\log \delta_c = 1.14 \log Cv - 2.33$ [mm, J] ductile failure [A.1.1]

$\log \delta_c = 1.30 \log Cv - 2.58$ [mm, J] brittle failure [A.1.2]

while for the weld metal:

$\log \delta_c = 1.06 \log Cv - 2.24$ [mm, J] ductile/quasi-cleavage failure [A.1.3]

Four data points were available for correlation [A.1.1], five for [A.1.2] and 14 for [A.1.3] (see Fig.A.1.1.1 and A.1.1.2). An accuracy of 95% is claimed for δ_c values predicted from Charpy impact data. The fracture toughness of the weld metal (with acicular ferrite micro-structure) was less sensitive to temperature changes, compared to the HAZ which was of coarse bainitic micro-structure.

A.2 LOWER-SHELF/TRANSITION CORRELATIONS

A.2.1 Tetelman, Wullaert and Ireland (1971) (A2)

Tetelman et al have developed a correlation based on the plastic zone size, which has been reviewed by Roberts et al (A34) and is applicable to lower-shelf static and dynamic fracture toughness of pressure vessel steels with yield strengths in the range from 270 to 814N/mm²:

$$K_{Ic,d} = 2.9\sigma_y\left[\exp\left(\frac{\sigma_f^*}{\sigma_y} - 1\right) - 1\right]^{\frac{1}{2}} \rho_o^{\frac{1}{2}} \quad \text{[units not specified]} \qquad [A.2.1]$$

where σ_y is the yield strength evaluated at the temperature and strain rate of interest, σ_f^* as the microscopic cleavage stress and ρ_o is the maximum notch root radius of which the fracture toughness is independent. Instrumented impact Charpy V notch specimens are used to determine K_{Id}, while slow-bend Charpy V notch specimens are used for K_{Ic}.

Tetelman et al maintain that at a temperature corresponding to a failure load of 80% of that required for general yield (P_{gy}), $\sigma_y = 33.3P_{gy}$ and $\sigma_f^* = 2.18\sigma_y$, from which Eq.[A.2.1] may be used to evaluate ρ_o. Charpy V notch specimens can be used to evaluate fracture toughness as long as $K_{Ic,d}/\sigma_y < 0.4$. Sporadic interest has been shown in this form of correlation (for example, Habashi et al (A46)), but these correlations are based on theoretical derivations which are difficult to understand and to apply in practice.

A.2.2 PVRC (1972) (A3)

The Pressure Vessel Research Committee (PVRC) have developed a method for determining a lower-bound toughness from the nil-ductility temperature (NDT) which is applicable to the lower-shelf and transition temperature range, and which has been reviewed by Pisarski (A35). This correlation is applicable to A533B-1 and A508 Class 2 and 3 steels (σ_y = 69.6ksi):

$$K_{IR} = 1.223 \exp(0.0145\ (T - NDTT + 160)) + 26.77$$

$$[ksi.in^{\frac{1}{2}},\ ^\circ F] \qquad [A.2.2.1]$$

where the reference stress intensity factor, K_{IR}, is a lower-bound of K_{Ic}, K_{Id} and K_{Ia} (crack initiation, propagation and arrest toughness), NDTT is the nil-ductility temperature, determined from standard drop-weight tests, and T is temperature. K_{IR} is restricted to less than 220ksi.in$^{\frac{1}{2}}$.

Rolfe and Barsom (A17) consider that the PVRC K_{IR} curve will provide adequate lower-bound toughness values for other ferritic steels with yield strength of less than 340N/mm^2 (A35).

Pisarski (A35) has discussed various attempts to evaluate NDT from Charpy impact tests, but warns that these can be unreliable, and may be non-conservative. This conclusion has been confirmed by Graville (A36), who has shown that NDT-Cv correlations are poor for low sulphur and carbon steels, although better correlation has been obtained for other steels. Graville has indicated that it is difficult to establish the structural significance of the drop weight test at temperatures away from the NDTT.

The PVRC correlation is illustrated in Fig.A.2.2.

A.2.3 Sailors and Corten (1973) (A4)

Sailors et al have developed correlations based on some of the data of Barsom and Rolfe (A15,A16), limiting the range of Charpy values to 7 to 70J, to decrease scatter in the data at lower values of Charpy energy (inertial effects) and to exclude any upper-shelf data. Thus, the correlation of Sailors et al is applicable to the transition regime, and to A533B, A542, A517F, A302B and ABS-C steels, with yield strengths in the range 410 to 815N/mm^2. These correlations have been reviewed by Pisarski (A35), Roberts et al (A34), Graville (A36) and Hertzberg (A37):

$$K_{Ic} = 15.5\ Cv^{\frac{1}{2}} \qquad [ksi.in^{\frac{1}{2}},\ ft.lb]$$

$$= 14.6\ Cv^{\frac{1}{2}} \qquad [MPa.m^{\frac{1}{2}},\ J] \qquad [A.2.3.1]$$

Correlation [A.2.3.1] was found to provide good estimates of toughness for A533B and A517F steels, but appeared to be over-conservative for welds in A517F steel. Sailors et al have also derived a correlation for dynamic fracture toughness, K_{Id}:

$$K_{Id} = 15.875\ Cv_{pci}^{0.375} \qquad [ksi.in^{\frac{1}{2}},\ ft.lb]$$

$$= 15.5\ \ Cv_{pci}^{0.375} \qquad [MPa.m^{\frac{1}{2}},\ J] \qquad [A.2.3.2]$$

Where Cv_{pci} is the fatigue pre-cracked Charpy impact energy. Sailors et al noted that data from standard Charpy specimens from A533B steel agreed with correlation [A.2.3.2] and concluded that notch acuity had limited effect on this correlation. Also, Sailors et al note that correlation [A.2.3.2] may be used to evaluate the static fracture toughness, K_{Ic}, if pre-cracked slow-bend Charpy specimens are employed. Correlations [A.2.3.1] and [A.2.3.2] are illustrated in Fig.A.2.3.1 and A.2.3.2.

A.2.4 ASME III, XI, Appendix G (1977, 1989) (A5,A6)

The K_{IR} reference stress intensity, concept of the PVRC (A3), reviewed in Section A.2.2, has been modified by ASME and Chirigos et al (A38) to construct a lower-bound to static fracture toughness, K_{Ic}, as reviewed by Pisarski (A35):

$$K_{Ic} = 2.806 \exp(0.02\ (T - NDT - 100)) + 33.194$$

[ksi.in^{½}, °F] [A.2.4.1]

This correlation is applicable to A533B-1 and A508 Class 2 and 3 steels (σ_y = 480N/mm^2), and is appropriate to the lower-shelf and transition temperature regime, limited to toughness values of less than 220ksi.in^{½}.

The current version of the ASME Boiler and Pressure Vessel Code, Section III, Appendix G recommends the following reference stress intensity curve (A5):

$$K_{IR} = 1.233 \exp(0.0145\ (T - RT_{NDT} + 160)) + 26.78$$

[ksi.in^{½}, °F] [A.2.4.2]

ASME also presents this relationship in graphical form (see Fig.A.2.4), and restricts the correlations to steels with yield strengths less than 50ksi (although Eq.[A.2.4.2] can be used for yield strengths up to 90ksi if specimens are extracted from steel of three different heats (A5)).

A.2.5 Matsumoto, Takai, Matsumura, Ogushi and Hamada (1978) (A7)

Matsumoto et al have developed a correlation between fracture toughness, K_{Ic}, and Charpy fracture appearance transition temperature (FATT) which is derived from data obtained from electroslag-welded joints of 110mm thick JIS SM41B and 100mm thick JIS SM50 steel plate (yield strengths not given). Both plates received post-weld heat treatment of two forms: annealed for stress-relief at 625°C for four hours, and furnace-cooled; and normalised at 910°C for two hours and air-cooled, and tempered at 625°C for four hours and furnace-cooled. The following lower-bound correlation is proposed, established from approximately 60 data points, including parent plate, weld metal and HAZ data:

$$K_{Ic} = 31 + 1.615 \exp[0.038 (Te_p + 140)] \qquad [MPa.m^{\frac{1}{2}}, °C] \qquad [A.2.5.1]$$

where $Te_p = T - FATT$, the 'excess' temperature (A7). T is the temperature at which K_{Ic} is to be evaluated, and FATT is the temperature at which the Charpy fracture surface has a 50% ductile/brittle appearance. This correlation is applicable to the lower-shelf and transition regimes, and is illustrated in Fig.A.2.5.

A.2.6 Imai, Nakaya, Yajima, Tada, Yamagata and Deguchi (1984) (A8)

Imai et al have developed a lower-shelf/transition K_{IC}-Cv correlation for 9% Ni steel weld metal (σ_y approximately 630N/mm^2) applicable in the temperature range of -196 to -40°C. The correlation of Imai et al is appropriate for Charpy impact energies in the range of 5 to 200J. The proposed correlation, which is a lower-bound of approximately 65 data points, including base metal and HAZ, is given by:

$$\frac{K_{Ic}^2}{\sigma_y} = 2.5Cv^{\frac{1}{2}} \qquad [MPa.m^{\frac{1}{2}},\ N/mm^2J] \qquad [A.2.6.1]$$

This correlation is illustrated in Fig.A.2.6.

A.3 TRANSITION CORRELATIONS

A.3.1 Logan and Crossland/Thorby and Ferguson (1971) (A9)

Logan et al have generated data for high strength steels (En25, 3%Ni-Cr-Mo-V), with yield strengths ranging from 820 to 1420N/mm², where they noted that a correlation exists between K_{Ic} and Cv. Thorby et al (A13) have applied a correlation to the data of Logan et al (A9) and this has been reviewed by Roberts et al (A34). This correlation is applicable in the transition regime, for Charpy energies in the range of 5.6 to 54J: (see Fig.A.3.1).

$$K_{Ic} \approx 18.2\left(\frac{Cv}{A}\right)^{\frac{1}{2}} \qquad [MPa.m^{\frac{1}{2}},\ J/cm^2]$$

$$\approx 43.6\left(\frac{Cv}{A}\right)^{\frac{1}{2}} \qquad [ksi.in^{\frac{1}{2}},\ ft.lb/in^2] \qquad [A.3.1.1]$$

where A is the cross sectional area of the Charpy specimen.

A.3.2 Kanazawa, Machida and Miyata (1974) (A10)

Kanazawa et al have established a temperature shift technique to account for the differences between the fracture toughness and the Charpy impact energy temperature transition curves. No specific correlation between K_{Ic} and Cv is presented. However, the temperature shift relation can be used in conjunction with other correlations, to account for some of the strain rate effects. Kanazawa et al have validated their results for mild steel, HY50, HY60 and HY80 steels (yield strengths for the HY series of steels are in the range 50 to 80kg/mm^2), including data from weld fusion lines (obtained from 66 data points):

$$\Delta T = (R - 1)FATT + 11.4t^{\frac{1}{4}} - 102 \quad [°K, mm] \qquad [A.3.2.1]$$

where

$$R = 0.0047\sigma_y + 0.56 \quad [kg/mm^2] \qquad [A.3.2.2]$$

FATT is the temperature at which the Charpy fracture face is 50% brittle/ductile in appearance, and t is the thickness of the specimen used for evaluating K_{Ic}. The performance of this temperature shift relationship is illustrated in Fig.A.3.2.

A.3.3 Barsom (1975) (A11)

Barsom has developed a series of correlations which are applicable to the lower-shelf and transition regimes (see also Section A.5.1). These correlations have been reviewed by Pisarski (A35), Roberts et al (A34), Graville (A36) and Hertzberg (A37). Barsom has used data from Barsom and Rolfe (A15,A16) for A8S-C, A302B, A305B and A517F steels. (σ_y in the range 270 to 760N/mm^2) in developing the AASHTO fracture toughness requirements for bridge steels. The following correlations have been presented by Barsom, between static and dynamic fracture toughness and various Charpy energies: (see Fig.A.3.3)

$$\frac{K_{Ic}}{E}^2 = 5\ Cv_{sb} \qquad \text{[psi.in, ft.lb]}$$

$$= 0.64\ Cv_{sb} \qquad \text{[kPa.m, J]} \qquad \text{[A.3.3.1]}$$

$$\frac{K_{Id}}{E}^2 = 5\ Cv \qquad \text{[psi.in, ft.lb]}$$

$$= 0.64\ Cv \qquad \text{[kPa.m, J]} \qquad \text{[A.3.3.2]}$$

$$\frac{K_{Ic}}{E}^2 = 4\ Cv_{psb} \qquad \text{[psi.in, ft.lb]}$$

$$= 0.52\ Cv_{psb} \qquad \text{[kPa.m, J]} \qquad \text{[A.3.3.3]}$$

$$\frac{K_{Id}}{E}^2 = 4\ Cv_{pci} \qquad \text{[psi.in, ft.lb]}$$

$$= 0.52\ Cv_{pci} \qquad \text{[kPa.m, J]} \qquad \text{[A.3.3.4]}$$

where Cv is the standard Charpy impact energy, Cv_{sb} refers to a slow-bend Charpy specimen, Cv_{psb} to a fatigue pre-cracked Charpy specimen, and Cv_{pci} refers to a precracked Charpy impact specimen. These correlations are applicable for Charpy energies in the range of 3 to 61J.

Barsom has also presented a technique for relating the Charpy impact energy, Cv, to the static fracture toughness, K_{Ic}, accounting for strain rate effects by shifting the temperature transition curves:

$$\Delta T = 215 - 1.5\sigma_y \qquad [°F, ksi]$$

$$= 119 - 0.12\,\sigma_y \qquad [°C, N/mm^2] \qquad [A.3.3.5]$$

for $250 < \sigma_y < 965 N/mm^2$. $\Delta T = 0°C$ for $\sigma_y > 965 N/mm^2$.

Roberts et al (A34) warn that standard tests have not been established to measure Cv_{sb}, Cv_{psb} and Cv_{pci}, and so correlations [A.3.3.1], [A.3.3.3] and [A.3.3.4] should be used with caution.

A.3.4 Marandet and Sanz (1977) (A12)

Marandet et al have proposed a correlation which has been derived from data for A533B and 2.25%Cr-1Mo plate and welds, E36, Mn-Mo-V cast steel, C-Mn-Nb-V and 12MDV C4-03M steels (σ_y in the range 215 to 1100N/mm^2). This correlation, which has been reviewed by Pisarski (A35) and Roberts et al (A34) is applicable to the transition regime (for Charpy fracture surfaces greater than 80% crystallinity) and for Charpy energies of 5 to 50J:

$$K_{Id,c} = 19\ Cv^{\frac{1}{2}} \qquad [MPa.m^{\frac{1}{2}},\ J]$$

$$= 20\ Cv^{\frac{1}{2}} \qquad [ksi.in^{\frac{1}{2}},\ ft.lb] \qquad [A.3.4.1]$$

Marandet et al have employed a temperature shift concept to relate the dynamic fracture toughness, K_{Id}, to the static, K_{Ic}: (see Fig.A.3.4)

$$T_{100} = 1.37\ T_{28} + 9 \qquad [°C]$$

$$T_{91} = 1.37\ T_{21} + 4 \qquad [°F] \qquad [A.3.4.2]$$

where T_{100} is the temperature at which K_{Ic} = 100MPa.m$^{\frac{1}{2}}$ (T_{91} corresponds to K_{Ic} = 91ksi.in$^{\frac{1}{2}}$) and T_{28} is the temperature at which Cv = 28J (T_{21} corresponds to Cv = 21ft.lb). Thus, K_{Ic} may be correlated to Cv by employing Eq.[A.3.4.1] and shifting the temperature transition curve with Eq.[A.3.4.2].

Roberts et al (A34) warn that the temperature correlation [A.3.4.2] is questionable, since a least-squares fit to the data of Marandet et al, by Roberts et al gave the following relationship:

$$T_{100} = 1.48\ T_{28} + 0.55 \qquad [°C]$$

$$T_{91} = 1.48\ T_{21} - 14 \qquad [°F] \qquad [A.3.4.3]$$

Also, Marandet et al have noted that temperatures corresponding to Charpy energies anywhere between 20 and 30J and K_{Ic} toughness values of 60 to 100MPa.m$^{\frac{1}{2}}$ present valid alternatives to Eq.[A.3.4.2]. For example:

$$T_{100} = 1.53\ T_{20} + 27.2 \qquad [°C]$$

$$T_{91} = 1.53\ T_{15} + 32 \qquad [°F] \qquad [A.3.4.4]$$

Roberts et al remark that the possibility of two or more such linear relationships highlight some of the futility and difficulty associated with empirical correlations.

A.4 TRANSITION/UPPER-SHELF CORRELATIONS

A.4.1 Thorby and Ferguson (1976) (A13)

Thorby et al have developed correlations which are derived from limited data for HY60 and two experimental steels (σ_y in the range 400 to 560N/mm²). These correlations, which have been reviewed by Roberts et al (A34), are applicable to the transition and upper-shelf regime (Charpy energies in the range 5 to 125J) and the transition regime (Charpy energies in the range 16 to 40J). For V notched Charpy specimens (see Fig.A.4.1):

$$K_c = 15\left(\frac{Cv}{A}\right)^{0.534} \qquad [MPa.m^{\frac{1}{2}},\ J/cm^2]$$

$$= 38\left(\frac{Cv}{A}\right)^{0.534} \qquad [ksi.in^{\frac{1}{2}},\ ft.lb/in^2] \qquad [A.4.1.1]$$

where A is the cross sectional area of the Charpy specimen. For fatigue notched Charpy specimens:

$$K_c = 25\left(\frac{Cv_{pci}}{A}\right)^{\frac{1}{2}} \qquad [MPa.m^{\frac{1}{2}},\ J/cm^2]$$

$$= 60\left(\frac{Cv_{pci}}{A}\right)^{\frac{1}{2}} \qquad [ksi.in^{\frac{1}{2}},\ ft.lb/in^2] \qquad [A.4.1.2]$$

where CV_{pci} is the impact energy of a Charpy specimen pre-cracked by fatigue. Roberts et al warn that only four data points have been used to define these correlations and so they should be used with caution.

A.4.2 **Oda (1988) (A14)**

Oda has developed δ_c Cv correlations which are applicable to a range of materials, including SS41 and HT80 steels, and A5083 aluminium alloy (yield strengths in the range of 276 to 834N/mm²). These correlations are applicable to a range of temperatures in the upper-shelf and transition regimes, and for Charpy impact energies in the range of 5 to 200J.

Oda has shown that the Cv and δ_c temperature transition curves show similar trends qualitatively, but are significantly different quantitatively. Oda has employed a temperature shift concept in order to correlate Cv and δ_c values over a range of temperatures. Two alternative correlations have been developed (obtained from approximately 40 data points, see Fig.A.4.2.1).

$$\delta_c = 3.44\times10^{-3}\ \ln(256\ Cv'/\sigma_y) \quad \text{[mm, J, N/mm}^2\text{] brittle regime}$$

$$\delta_c = 1.8\ Cv'/\sigma_y - 0.1 \quad \text{[mm, J, N/mm}^2\text{] ductile regime} \qquad \text{[A.4.2.1]}$$

An alternative pair of correlations have been proposed by Oda:

$$\delta_c = 10\sigma_y\ [\ln(E\ Cv'/\sigma_y^2)]/E \quad \text{[mm, N/mm}^2\text{, J] brittle regime}$$

$$\delta_c = 1.67\ Cv'/\sigma_y - 21.7\sigma_y/E \quad \text{[m, J, N/mm}^2\text{] ductile regime} \qquad \text{[A.4.2.2]}$$

To evaluate δ_c at a temperature T, the Charpy impact energy Cv' is evaluated at a temperature T + ΔT, where ΔT is the transient temperature shift:

$$\Delta T = {}_vT_{RS} - T_f \qquad \text{[A.4.2.3]}$$

where ${}_vT_{RS}$ is the temperature (in °C) at which the Charpy fracture surface has 50% shear appearance, and T_f is the temperature at which a brittle fracture initiates in the Charpy specimen (which corresponds roughly to temperatures at which $\delta_c = \delta_i$ (≈0.16mm). ΔT has been evaluated as 72°C for SS41, 39°C for HT80 (1) (σ_y = 786N/mm²), 108°C for HT80 (2) (σ_y = 834N/mm²), and 0°C for A5083.

Both correlations [A.4.2.1] and [A.4.2.2] give similar results, with both giving marginally better correlations in the ductile regime.

A.4.3 Miscellaneous NDTT Correlations

The dynamic fracture toughness has been correlated with the dynamic yield strength at the nil-ductility transition temperature (NDTT). Roberts et al (A34) have reviewed pre-1980 correlations based on NDTT. Most of the correlations considered by Roberts et al apply only at the NDTT temperature, and one cannot, in general, predict the entire temperature transition curve.

From the examination of many broken NDTT specimens, Irwin et al (A39) estimated the length-to-depth ratio of the semi-elliptical crack in the specimen to be 4:1. Using this value, an approximate stress analysis yielded:

$$K_{Id}\ (NDTT) = c\ \sigma_{yd} \qquad [MPa.m^{\frac{1}{2}},\ N/mm^{\frac{3}{2}}] \qquad [A.4.3.1]$$

where σ_{yd} is the dynamic yield strength and the constant $c = 0.12m^{\frac{1}{2}}$. Pellini (A40) observed that the length-to-depth ratio of the crack was closer to 3:1, with the resulting constant in Eq.[A.4.3.1] $c = 0.11m^{\frac{1}{2}}$. Rolfe et al (A17) have attributed a value to this constant of $c = 0.10m^{\frac{1}{2}}$, based on the average result for seven steels presented by Shoemaker et al (A41). (For most of these seven steels c ranged from 0.096 to $0.11m^{\frac{1}{2}}$). Rolfe et al (A17) suggested a value of $c = 0.096m^{\frac{1}{2}}$ as a reasonably conservative correlation. Also, Rolfe et al (A17) provide a method for estimating the dynamic yield strength:

$$\sigma_{yd} = \sigma_y + 172 \qquad [N/mm^2] \qquad [A.4.3.2]$$

where σ_y is the quasi-static yield strength. Roberts et al comment that there is insufficient data to evaluate these correlations adequately.

A.5 UPPER-SHELF CORRELATIONS

A.5.1 Barsom, Rolfe and Novak (1970) (A15,A16,A17)

Barsom et al and Rolfe et al have developed two correlations, one of which is applicable to the transition regime, and the other to the upper-shelf. These correlations have been reviewed by Pisarski (A35), Roberts et al (A34), Graville (A36) and Hertzberg (A37).

The following transition correlation (see also Section A.3.3) has been derived from data for HY80, 18Ni-8Co-3Mo A302B, A517F, A3202B, ABS-C, HY130, 18Ni (250), Ni-Cr-Mo-V, Cr-Mo-V and Ni-Mo-V steels (σ_y in the range 270 to 1700N/mm^2), and Charpy impact energy in the range 4 to 82J):

$$\frac{K_{Ic}^2}{E} = 0.22\ Cv^{3/2} \qquad \text{[kPa.m, J]}$$

$$= 2\ Cv^{-3/2} \qquad \text{[psi.in, ft.lb]} \qquad \text{[A.5.1.1]}$$

For A517F, 4147, HY130, 4130, 12Ni-5Cr-3Mo, 18Ni-8Co-3Mo and A517D steels (σ_y in the range 760 to 1700N/mm^2) in the upper-shelf regime, the following correlation has been developed, which is applicable to Charpy energies in the range 31 to 121J, with all tests conducted at 27°C:

$$\left(\frac{K_{Ic}}{\sigma_y}\right)^2 = 0.64\left[\frac{Cv}{\sigma_y} - 0.01\right] \qquad \text{[m, J,N/mm}^2\text{]}$$

$$= 5\left[\frac{Cv}{\sigma_y} - 0.05\right] \qquad \text{[in, ft.lb]} \qquad \text{[A.5.1.2]}$$

Pisarski (A35) has warned that not all of the K_{Ic} specimens of Rolfe et al were of sufficient size to ensure plane strain, and so valid K_{Ic} values were not always obtained.

Roberts et al (A34) have fitted a lower-bound correlation to the data of Barsom et al and Rolfe et al, which corresponds to a 95% confidence level, obtained by lowering the best fit by two standard deviations:

$$\left(\frac{K_{Ic}}{\sigma_y}\right)^2 = 0.64\left[\frac{Cv}{\sigma_y} - 0.02\right] \qquad \text{[m, J/Mpa]}$$

$$= 5\left[\frac{C_v}{\sigma_y} - 0.1\right] \qquad \text{[in, ft.lb/ksi]} \qquad \text{[A.5.1.3]}$$

Roberts et al have repeated this exercise for data from Ault et al (A18), and for the data of Barsom et al, Rolfe et al and Ault et al combined. These correlations may be found elsewhere in this report. The correlations [A.5.1.1.] and [A.5.1.2] of Barsom et al are illustrated in Fig.A.5.1.1 and A.5.1.2.

A.5.2 Ault, Waid and Bertolo (1971) (A18)

Ault et al have developed an upper-shelf correlation which is similar in form to that of Barsom et al [A15,A16,A17] and which is reviewed by Roberts et al (A34). This correlation is applicable to high strength steels (σ_y in the range 1610 to 1980N/mm^2), and for a range of Charpy impact energies of 15 to 28.6J: (see Fig.A.5.2).

$$\left(\frac{K_{Ic}}{\sigma_y}\right)^2 = 0.18\left(\frac{Cv}{\sigma_y}\right) - 0.0011 \qquad \text{[m, J,N/mm}^2\text{]}$$

$$= 1.37\left(\frac{Cv}{\sigma_y}\right) - 0.045 \qquad \text{[in, ft.lb/ksi]} \qquad \text{[A.5.2.1]}$$

This correlation appears to be more generally conservative than that of Barsom et al (A15,A16,A17). Roberts et al (A34) have fitted lower-bound correlations to the data of both Ault et al and Barsom et al, and to their combined data. These correlations represent a lower-bound confidence level of 95% (formed by lowering the best fit to the data by two standard deviations). For the data of Ault et al:

$$\left(\frac{K_{Ic}}{\sigma_y}\right)^2 = 0.17\left(\frac{Cv}{\sigma_y}\right) - 0.0015 \qquad \text{[m, J/MPa]}$$

$$= 1.3\left(\frac{Cv}{\sigma_y}\right) - 0.06 \qquad \text{[in, ft.lb/ksi]} \qquad \text{[A.5.2.2]}$$

while for the combined data of Ault et al and Barsom et al:

$$\left(\frac{K_{Ic}}{\sigma_y}\right)^2 = 0.52\left(\frac{Cv}{\sigma_y} - 0.02\right) \qquad \text{[m, J,MPa]}$$

$$= 4.0\left(\frac{Cv}{\sigma_y} - 0.1\right) \qquad \text{[in, ft.lb/ksi]} \qquad \text{[A.5.2.3]}$$

The lower-bound fit of Roberts et al to the data of Barsom et al alone is given in Section 5. Roberts et al warn that K_{Ic} results from J_{Ic} testing may not be compatible with these correlations.

A.5.3 Norris, Beaugh and Server (1981) (A19)

Norris et al have developed upper-shelf correlations between Charpy impact and initiation energies (Cv and Cv_i) and fracture toughness, J_{Ic}. These correlations have been evaluated for data on 23 steels (mostly from the literature: Rolfe, Novak and Barsom (A15,A16,A17); and Server (A42)) with yield strengths in the range 447 to 1696N/mm², and are applicable to Charpy impact energies of 22 to 192J.

In the upper-shelf regime typically only 10% of the total absorbed energy, Cv, of the impact Charpy test is associated with crack initiation, while 90% is associated with crack propagation (A19). In order to achieve better J_{Ic}-Cv correlation, Norris et al examined the slow-bend Charpy initiation energy, Cv_{sbi} of 267mm thick SA533B-1 steel plate at 100°C, to establish the following correlation (from 30 data points):

$$J_{Ic} \approx 15.1\ Cv_i \qquad [kN/m,\ J] \qquad [A.5.3.1]$$

Norris et al found that a linear relationship existed between the ratio Cv_i/Cv and σ_y for the SA533B-1 material. Combining this relationship with Eq.[A.5.3.1] gives:

$$J_{Ic} \approx Cv\left(\frac{\sigma_y + 1600}{1300}\right) \qquad [kN/m,\ J,\ N/mm^2] \qquad [A.5.3.2]$$

The accuracy of fracture toughness predictions using the above correlation compared favourably with the correlations of Rolfe et al (A15,A16,A17). Correlation [A.5.3.1] is illustrated in Fig.A.5.3.

A.5.4 Priest, Charnock and Stewart (1982) (A20)

Priest et al have investigated the fracture toughness of irradiated C-Mn pressure vessel steel (irradiation doses of $5x10^{17}$-$5x10^{18}$n.cm^{-2} at 180°C (E > 1MeV). Upper-shelf K_{IC}-Cv correlations have been obtained for both parent metal (σ_y in the range 190 to 320N/mm^2) and submerged-arc weld metal (σ_y in the range 290 to 450N/mm^2). The correlations of Priest et al are applicable to Charpy impact energies in the range 5 to 120J.

Priest et al have shown that the correlation of Barsom and Rolfe (A15,A16,A17) is applicable to the weld metal (obtained for approximately 13 data points):

$$\left(\frac{K_{IC}}{\sigma_y}\right)^2 = 0.65\left(\frac{Cv}{\sigma_y}\right) - 0.0063 \qquad [MPa.m^{\frac{1}{2}},\ N/mm^2,\ J] \qquad [A.5.4.1]$$

Priest et al have derived a modified form of the Barsom and Rolfe correlation which is applicable to the parent plate (obtained from 5 data points):

$$\left(\frac{K_{IC}}{\sigma_y}\right)^2 = 1.622\left(\frac{Cv}{\sigma_y}\right) - 0.011 \qquad [MPa.m^{\frac{1}{2}},\ N/mm^2,\ J] \qquad [A.5.4.2]$$

Priest et al have shown that the effect of irradiation on the initiation fracture toughness is minimal, and so the correlations presented above apply to both irradiated and non-irradiated materials. Correlation [A.5.4.2] is illustrated in Fig.A.5.4.

A.5.5 Witt (1983) (A21)

Witt has developed several lower-bound upper-shelf K_{Ic}-Cv correlations derived from a set of 41 data points from A533B Class 1, A508 Class 2, A302B, Ni-Cr-Mo and A516 Grade 70 steels (yield strengths in the range 414 to 848N/mm^2). Various notch orientations were included, and manual metal arc and submerged arc welds were considered.

Witt has considered two correlations, the first of which is based on a simple least-squares linear fit to the data:

$$K_{Ic} = 2.78\ Cv - 3.93 \qquad [MPa.m^{\frac{1}{2}},\ J]$$

$$= 3.43\ Cv - 3.58 \qquad [ksi.in^{\frac{1}{2}},\ ft.lb] \qquad [A.5.5.1]$$

Correlation [A.5.5.1] is applicable to Charpy energies in the range 102 to 203J, and Witt warns against extensive extrapolation. Secondly, Witt has employed a concept he terms the 'volumetric energy ratio' to account for differences in specimen size (K_{Ic} specimens). This analysis gives:

$$K_{Ic} = (0.068\ Cv + 9.90)^2 \qquad [MPa.m^{\frac{1}{2}},\ J]$$

$$= (0.088\ Cv + 9.45)^2 \qquad [ksi.in^{\frac{1}{2}},\ ft.lb] \qquad [A.5.5.2]$$

Correlation [A.5.5.2] is applicable to Charpy energies in the range 47 to 203J, and gives very similar results to correlation [A.5.5.1] in the range 102 to 203J. This correlation should not be employed for Charpy energies less than 47J, where there is a possibility of brittle cleavage in the transition regime. Correlation [A.5.5.2] is illustrated in Fig.A.5.5.

A.6 LOWER-SHELF/TRANSITION/UPPER-SHELF CORRELATIONS

A.6.1 Begley and Logsdon (1971) (A22)

The correlation of Begley et al has been reviewed by Pisarski (A35) and Roberts et al (A34), and is applicable to turbine rotor steels Ni-Cr-Mo-V, Ni-Mo-V and 12Cr-Mo-V (σ_y in the range 620 to 965N/mm^2). Begley et al have modelled the entire temperature transition curve with four straight line segments.

Begley et al have determined that at a temperature which corresponds to 100% brittle fracture of the Charpy specimen, the material toughness can be related to the yield strength of the material:

$$K_{IC} = 0.45\ \sigma_y \qquad [\text{ksi.in}^{\frac{1}{2}},\ \text{ksi}] \qquad [A.6.1.1]$$

Begley et al recommend the use of the upper-shelf correlation of Barsom et al (A15,A16,A17) (reviewed in Section A.5.1), for temperatures greater than that which correspond to 100% ductile fracture of the Charpy specimen. A toughness representing the middle of the transition curve is taken as the average of the upper- and lower-shelf values, at a temperature corresponding to 50% ductile/brittle fracture of the Charpy specimen. A toughness of 25ksi.in$^{\frac{1}{2}}$ is presumed at a temperature of -196°C. Using the toughness values determined in this fashion, the entire temperature transition can be represented by four straight line segments.

A.6.2 Oldfield, Server and Wullaert (1980, 1984) (A23),A43),A44)

Oldfield et al have developed a referencing procedure which permits statistical-bounds to be predicted to fracture toughness from Charpy V notch test data. Oldfield et al have proposed that the standard reference curve, which is of the form:

$$K_{IR} = 29.43 + 1.344 \exp[0.2611(T_{ref} + 106)]$$

[MPa.m$^{\frac{1}{2}}$, °C] [A.6.2.1]

should be replaced with an hyperbolic tangent (tanh) function of the form:

$$K_{IR} = a + b \tanh\left(\frac{T - T_o}{c}\right) \qquad [A.6.2.2]$$

where a, b, c and T_o, are constants determined by a statistical regression analysis. This function has a characteristic 's' shape which corresponds to the entire temperature transition curve, as shown in Fig.A.6.2.1. (Function [A.6.2.1] has a characteristic 'J' shape, as shown in Fig.A.6.2.2). K_{IR} is the lower-bound of static, dynamic and crack arrest toughness (K_{Ic}, K_{Id} and K_{Ia}). The tanh function can, of course, be applied to K_{Ic}, K_{Id} and K_{Ia} separately. A similar tanh function may be used to describe the Cv temperature transition curve. Oldfield et al have derived relationships between the K_{IR} tanh function constants and the Cv tanh function constants, to establish a K_{IR}-Cv correlation.

Most of the data used by Oldfield et al applied to the transition and upper-shelf, and so a lower-shelf toughness of 0.80lMPa.m$^{\frac{1}{2}}$ was assumed (a weighted average of the lower-shelf data used by Oldfield et al), which reduced Eq.[A.6.2.2] to a three parameter function.

Oldfield et al have used a large set of data (more than 100 data points) relating to pressure vessel steels (details not given), together with a toughness-Charpy correlation of the form $K_{Ic,d,a} = (ECv)^{\frac{1}{2}}$ to establish the constants in Eq.[A.6.2.2] for lower-bound curves at various confidence levels.

The details of these techniques are too extensive to present here. However, the method does represent a significant advance in the ability to predict fracture toughness from Charpy results to a given level of confidence over the entire temperature transition curve. The reader is referred to the papers by Oldfield et al (A23), Oldfield (A43) and Wullaert et al (A43) for details. The statistically based reference toughness methods developed by Oldfield et al have been applied and evaluated for various pressure vessel steels, including welds and irradiated steels in other papers in the same volume as

that of Oldfield et al. These materials include SA533B, SA508, SA516, SA515, SA543, SA516, A7, A285, A441, A572, A588, A612, A633, A387 and many other low and high strength alloys.

A.6.3 Richardson, Server and Rauter (1985) (A24)

Richardson et al have evaluated the adequacy of predicting K_{IC}, NDTT, RT_{NDT}, T_{68J} and T_6 from the Charpy temperature transition curves. The effects of notch orientation were also considered. Materials considered included SA533B-1 steel plate and SA-508-2 steel forgings, including manual metal arc and submerged-arc welds in these steels. Richardson et al have assumed a Charpy temperature transition curve of the form:

$$Cv = a + b \tanh\left(\frac{T - T_o}{c}\right) \qquad [A.6.3.1]$$

where a, b, c and T_o are curve fitting parameters. Approximately 20 Charpy specimens were used from each plate, forging or weld. Richardson et al have employed statistical techniques and engineering judgement to determine correlations between NDTT, RT_{NDT}, T_{68J} and T_6, usually in the form of a lower-bound curve (95% confidence level). The results of Richardson et al are presented in graphical form, and the reader is referred to their paper for details. See Fig.A.6.3.1, A.6.3.2 and A6.3.3 for examples of the correlations of Richardson et al.

A.6.4 Girenko and Lyudin (1985) (A25)

Girenko et al have developed a series of dimensionally consistent correlations between Charpy impact energies and the fracture toughness parameters K_{Ic} and δ_{Ic}, which is the measured plane strain CTOD. The correlations of Girenko et al are based on more than 100 data points for St3ps, St3sp, 09G2S, 14G2Af, 16G2AF, 15KL2MFA, 18Ni, A527F and ABS-C (yield strengths in the range 200 to 1700N/mm^2), including data from welds, with various heat treatments. Girenko et al present the following correlation, which represents a mean fit to parent plate data:

$$K_{Ic} = \left(\frac{5}{20}\,\frac{E}{1-\nu^2}\,\frac{Cv}{A}\right)^{\frac{1}{2}} \qquad [\text{Mpa.m}^{\frac{1}{2}},\ \text{N/mm}^2,\ J,\ \text{mm}^2] \qquad [A.6.4.1]$$

For a more conservative lower-bound estimation of fracture toughness:

$$K_{Ic} = \left(0.1\,\frac{E}{1-\nu^2}\,\frac{Cv}{A}\right)^{\frac{1}{2}} \qquad [\text{Mpa.m}^{\frac{1}{2}},\ \text{N/mm}^2,\ J,\ \text{mm}^2] \qquad [A.6.4.2]$$

For welds:

$$K_{Ic} = \left(0.1\,\frac{E}{1-\nu^2}\,\frac{Cv}{A}\right)^{\frac{1}{2}} - 15 \qquad [\text{Mpa.m}^{\frac{1}{2}},\ \text{N/mm}^2,\ J,\ \text{mm}^2] \qquad [A.6.4.3]$$

These correlations are applicable to both the ductile and brittle fracture regimes, although correlation [A.6.4.3] is recommended for welded joints in the brittle regime, to ensure conservative estimates of K_{Ic}. The reader is referred to the paper by Girenko et al, where Eq.[A.6.4.1] to [A.6.4.3] are presented in terms of δ_{Ic}, the critical plane strain CTOD. Correlations [A.6.4.1] to [A.6.4.3] are illustrated in Fig.A.6.4.

A.6.5 BSI PD6493 (1991) (A26)

BSI PD6493:1991 Appendix B recommends that fracture toughness should only estimated by correlation with Charpy impact energies if fracture toughness data cannot be obtained. PD6493 presents two correlations: one to describe the lower-shelf and transition regime; and one for the upper-shelf, both given in a graphical form (Fig.28(a) and (b) in PD6493, Fig.A.6.5.1 and A.6.5.2 below). These correlations are based on the lower-bound of test data for ASTM A533B steel. This correlation has been shown, in general, to be representative for other steels and weld metals, except for some thick section materials (A26).

Figure 28(a) of PD6493 correlates K_{Ic} with the temperature shift between the temperature of interest and the temperature at which a Charpy impact energy of 40J is recorded. This correlation is exactly the same as the PVRC/ASME correlation (Sections A.2.2 and A.2.4), if $T_{40J} = RT_{NDT}$.

Figure 28(b) correlates directly the upper-shelf Charpy impact energy with fracture toughness, K_{Ic}. The lowest estimate of K_{Ic} obtained from Fig.28(a) and (b) should be used.

A.7 OTHER CORRELATIONS

A.7.1 Hartbower, Reuter and Crimmons (1968) (A27)

The correlation of Hartbower et al has been reviewed by Roberts et al (A34). Instrumented pre-cracked Charpy impact and slow-bend specimens have been employed by Hartbower et al to develop correlations which are applicable to Ti-6Al-4V alloy, although no indication is given by Roberts et al as to the temperature, Charpy energy and yield strength ranges over which the correlations are applicable. The following correlations are presented:

$$K_{Ic} = 0.52\left(\frac{Cv_{pi}}{A}\right) + 7.4 \qquad [MPa.m^{\frac{1}{2}},\ J/cm^2]$$

$$K_{Ic} = 0.1\left(\frac{Cv_{pi}}{A}\right) + 6.7 \qquad [ksi.in^{\frac{1}{2}},\ ft.lb/in^2] \qquad [A.7.1.1]$$

$$K_{Ic} = 0.89\left(\frac{Cv_{sb}}{A}\right) + 17.8 \qquad [MPa.m^{\frac{1}{2}},\ J/cm^2]$$

$$K_{Ic} = 0.17\left(\frac{Cv_{sb}}{A}\right) + 16.2 \qquad [ksi.in^{\frac{1}{2}},\ ft.lb/in^2] \qquad [A.7.1.2]$$

where Cv_{pi} is the instrumented pre-cracked Charpy impact energy, Cv_{sb} is the instrumented pre-cracked slow-bend Charpy energy, and A is the cross-sectional area of the Charpy specimen. Roberts et al (A34) warn that no standard procedures exist for measuring Cv_{pi} and Cv_{sb}.

A.7.2 Ronald, Hall and Pierce (1972) (A28)

Ronald et al have developed a correlation which has been reviewed by Roberts et al (A34), derived from data for steel, titanium and aluminium alloys. This correlation is applicable to Charpy energies in the range 3 to 16J. However, Roberts et al do not indicate the yield strength or temperature range over which this correlation is applicable, or how many data points were used in its derivation:

$$K_{Ic}^2 \approx \frac{E}{2(1-\nu^2)} \frac{Cv_{psb}}{A} \quad [Nmm^{-3/2}, N/mm^2, J/mm^2] \qquad [A.7.2.1]$$

where Cv_{psb} is the fatigue pre-cracked slow-bend Charpy energy. Roberts et al comment that there is some theoretical basis for this correlation (it is dimensionally consistent), and that it fits the data well for Charpy energies in the range 3 to 11J/cm^2.

A.7.3 Ito, Tanaka and Sato (1973) (AJ9)

Ito et al have developed a correlation which is applicable to welded low alloy quenched and tempered steels (Welten 80, 62 and 60, A302B, A517F, HY130 and HY250, with yield strengths in the range 386 to 1025N/mm²). This correlation, which has been reviewed by Pisarski (A35), has been derived from data obtained from weld fusion lines, but is also applicable to plain alloy steels: (see Fig.A.7.3).

$$\left(\frac{K_{Ic}}{100}\right)^2 = 300\left(\frac{Cv}{\sigma_y}\right) \qquad \text{[kg.mm}^{-3/2}\text{, kg.m, kg/mm}^2\text{]} \qquad \text{[A.7.3.1]}$$

Pisarski (A35) comments that specimens used in deriving these correlations were of insufficient thickness to ensure plane strain, and so an empirical relationship was used to establish K_{Ic} values from K_c results.

A.7.4 **NMAB (1976) (A30)**

The National Materials Advisory Board (NMAB) have developed a correlation between static fracture toughness, K_{Ic}, and fatigue pre-cracked slow-bend Charpy energy, which has been reviewed by Roberts et al (A34). The NMAB correlation has been derived from data for steel, aluminium and titanium alloys (yield strengths in the range 310 to 2060N/mm^2). This correlation is applicable to Charpy energies in the range 0.6 to 33J, and is derived from a large data set:

$$\frac{K_{Ic}}{E}^2 = 0.95 + 0.45\left(\frac{Cv_{psb}}{A}\right) \qquad [MPa.m,\ J/cm^2]$$

$$= 5.4 + 0.342\left(\frac{Cv_{psb}}{A}\right) \qquad [ksi.in,\ ft.lb/in^2] \qquad [A.7.4.1]$$

Also, NMAB have presented the following correlation which relates the load at fracture (P_f) from an instrumented Charpy V notch impact test for low to medium strength steels, in the transition regime.

$$K_{Ic} = 0.03\ P_f \qquad [MPa.m^{\frac{1}{2}},\ kg]$$

$$= 0.2\ P_f \qquad [psi.in^{\frac{1}{2}},\ lb] \qquad [A.7.4.2]$$

A.7.5 Nogata and Takahashi (1986) (A31)

Nogata et al have developed a K_{IC}-Cv correlation, which is specifically concerned with the effects of irradiation embrittlement on reactor pressure vessel steels (SA533B and 22Ni-MoCr-37 weld metal, yield strengths not given). The strain-rate/temperature effect on the cleavage-controlled fracture toughness transition has been investigated, and dynamic toughness correlations (K_{Id}-Cv) developed. For the non-irradiated material, a temperature range of -160 to 160°C has been considered, which encompasses the entire temperature transition curve. For the irradiated material, a temperature range of 160°C to 400°C has been considered. Charpy impact temperatures range from approximately 5 to 196J. Radiation dosages have not been presented.

The correlations of Nogata et al are of the general form:

$$K_{IC} = a\left(\frac{Cv_{us}}{Cv} - 1\right)^b + c \qquad [MPa.m^{\frac{1}{2}}] \qquad [1]$$

where Cv_{us} is the upper-shelf Charpy impact energy. For non-irradiated SA533B, Cv_{us} = 196J, a = 139, b = -0.54 and c = 20 (obtained from 23 data points). For irradiated SA533B, Cv_{us} = 100J, a = 159, b = -0.62 and c = 20 (obtained from approximately 25 data points). For irradiated 22Ni-MoCr-37 weld metal, Cv_{us} = 135J, a = 167, b = -0.63 and c = 20 (obtained from 18 data points).

A.7.6 Yi, Sun-Wen, Hai-Ji and Xiao-Hai (1987) (A32)

Yi et al have developed K_{IC}-Cv correlations for two grades of mild steel (20# (σ_y = 265MPa) and 40# (σ_y = 410MPa), where '#' is notation used by Yi et al). In order to overcome uncertainties associated with notch acuity, fatigue pre-cracked Charpy specimens were employed, side-grooved to ensure plane strain conditions at the crack tip. The correlations of Yi et al are applicable to Charpy impact energies of 2 to 33J. No indication is given as to the temperature range over which these correlations are applicable.

Yi et al have developed a dimensionally consistent correlation permitting non-standard Charpy specimens could be used:

$$K_{IC} = \frac{10}{W}\frac{(Cv\ \sigma_y)}{\phi\left(\frac{a}{W}\right)}\left(\frac{B}{B_n}\right) \quad [kgf.mm^{3/2},\ mm,\ kgf.m,\ N/mm^2] \qquad [A.7.6.1]$$

where $\phi\left(\frac{a}{W}\right)$ is a geometrical factor determined experimentally for two Charpy specimen sizes (B = W = S), obtained from 32 data points:

1) 45 < 18 < 72mm: $\phi_1\left(\frac{a}{W}\right) = 0.651 - 0.612\left(\frac{a}{W}\right) + 2S_1$

2) 10 < 10 < 40mm: $\phi_2\left(\frac{a}{W}\right) = 0.561 - 0.637\left(\frac{a}{W}\right) + 2S_2$ [A.7.6.2]

where (a/W) is the ratio of crack depth to specimen width, and S_1 = 0.025 and S_2 = 0.031, standard error estimates included to ensure that the correlation is conservative. The specimen dimensions have been chosen such that S = 4W, and the specimens have been side grooved such that $B_n = B_0/B = 0.3$, where B_0 is the dimension between the side grooves.

A.7.7 Nageswara Rao and Acharya (1989) (A33)

Nageswara Rao et al have developed a dimensionally consistent K_{IC}-Cv correlation which is applicable to welded M250 grade (18% Ni) maraging steel (σ_y = 1610N/mm²), Ti-6Al-4V titanium alloy (σ_y = 930N/mm²) and 15CD9S steel (σ_y = 1060N/mm²). No indication has been given by the authors as to the temperature range over which their correlation is applicable. Charpy impact energies ranged from 19 to 23J for M250 steel, 18 to 22J for Ti-6Al-4V and 94 to 121J for 15CD9S steel.

Nageswara Rao et al have derived a non-dimensional correlation so that non-standard sized Charpy specimens could be used (for materials of thickness less than 10mm):

$$\left(\frac{K_{IC}}{\sigma_y}\right)^2 \left(\frac{E}{C_v}\right)^{1/2} = a \qquad [MPa.m^{\frac{1}{2}}, N/mm^2, J] \qquad [A.7.7.1]$$

where a = 13.09 for M250 steel (7.5 < B < 10 < 15mm specimens, obtained from 7 data points)

a = 11.84 for Ti-6Al-4V alloy (8 < B < 10 < 25mm specimens, obtained from 8 data points, including 2 EB welds)

a = 33 for 15CD9S steel (10 < B < 10 < 15mm specimens, obtained from 4 data points)

Errors in estimated K_{IC} values appear to be less than 5% for the materials tested by Nageswara Rao et al.

Anil Kumar et al (A65) have recently suggested that a statistical procedure be adopted, based on Eq.[A.7.7.1], to quantify the effects of variability of yield strength and Charpy energy data on the predicted fracture toughness.

Anil Kumar et al have applied these techniques to welded plates of M250 Grade (18% Ni) maraging steel, and have evaluated correlation [A.7.7.1] from 30 7.5 < B < 10 < 55 Charpy V notch specimens and 20 CT fracture toughness specimens. Anil Kumar et al have found that the fracture toughness evaluated in this fashion can be determined, on average, to within a tolerance of ±11% (based on confidence levels of 99.9%).

A.0 REFERENCES

A1 Chaudhuri S K, Ojha S N, Ramaswamy V: 1986, 'Fracture toughness evaluation of weldments and correlations with the Charpy data of a micro-alloyed steel', Int J Pres Ves & Piping, 23, 23-50.

A2 Tetelman A S, Wullaert R A, Ireland D: 1971, 'Prediction of variation in fracture toughness from small specimen tests', Practical Applications of Fracture Mechanics to Pressure Vessel Technology, Institution of Mechanical Engineers, 83-92. Cited by Roberts R, Newton C: 1981, Welding Research Council Bulletin, 265, 1-18.

A3 PVRC: 1972, Recommendations on 'toughness requirements for ferritic materials', Welding Research Council Bulletin, 175, August.

A4 Sailors R H, Corten H T: 1973, 'Relationship between material fracture toughness using fracture mechanics and transition temperature tests', ASTM-STP-514, 164-191.

A5 ASME Boiler and Pressure Vessel Code, Section III - 'Rules for construction of nuclear power plant components', 1989, 372-377.

A6 ASME Boiler and Pressure Vessel Code, Section XI - 'Rules for in-service inspection of nuclear power plant components', Division 1, 1977 Ed. Cited by Pisarski H G: 1978, The Welding Institute Research Bulletin, 19, (12), 362-367.

A7 Matsumoto K, Takai K, Matsumura S, Oguchi T, Yamada O: 1978, 'Effect of post-weld heat treatment on fracture mechanics properties of electroslag-welded joints of low carbon steel plates', 2nd Int Symp of Japan Welding Soc: Criteria for preventing service failures in welded structures, 26-28 Sep 1978, Tokyo, JWS, 167-172.

A8 Imai S, Nonaka I, Fujima S, Tada M, Yamagata S, Ohguchi A: 1984, 'Safety evaluation of LNG storage tanks of 9% Ni steel based on fracture analysis', Proc: Transport and storage of LPG and LNG, 1, Brugge 7-10 May 1984, 91-100.

A9 Logan J G, Crossland B: 1971, 'The fracture toughness of (En23) and a 12Ni-Cr-Mo-V steel at various strength levels together with Charpy impact data', Practical Applications of Fracture Mechanics to Pressure Vessel Technology, Institution of Mechanical Engineers, 148-155.

A10 Kanazawa T, Machida S, Miyata T: 1974, 'Present status on the evaluation criteria of fracture toughness for structural steels and their welded joints in Japan', Proc of an Int Conf on Prospects of Fracture Mechanics, Ed: Sih G C, van Elst H C, Broek D, Delft University of Technology, The Netherlands, June 24-28, 1974, 547-561.

A11 Barsom J M: 1975, 'Development of the AASHTO fracture mechanics requirements for bridge steels', Engineering Fracture Mechanics, **7**, 605-618.

A12 Marandet B, Sanz G: 1977, 'Evaluation of the toughness of thick medium strength steels by LEFM and correlations between K_{Ic} and CVN', ASTM-STP-631, 72-95.

A13 Thorby P N, Ferguson W G: 1976, 'The fracture toughness of HY60', Materials Science and Engineering, **22**, 177-184.

A14 Oda I: 1988, 'Inference of critical COD from Charpy V test result', Eng Frac Mech, **29**, (6), 663-671.

A15 Barsom J M, Rolfe S T: 1970. 'Correlations between K_{Ic} and Charpy V notch test results in the transition temperature range', ASTM-STP-466, 281-302.

A16 Rolfe S T, Novak S T: 1970, 'Slow bend K_{Ic} testing of medium strength high toughness steels', ASTM-STP-463, 124-159. Cited by Pisarski H G: 1978, The Welding Institute Research Bulletin, **19**, (12), 362-367.

A17 Rolfe S T, Barsom J M: 1977, Fracture and fatigue control in structures - application of fracture mechanics, Prentice-Hall. Cited by Roberts et al: 1981, Welding Council Research Bulletin, **265**, 1-18.

A18 Ault R T, Waid G M, Bertolo R B: 1971, 'Development of an improved ultra-high strength steel for forged aircraft components', AFML-TR-71-27, Air Force Materials Laboratory.

A19 Norris D M, Reaugh J E, Server W L: 1981, 'A fracture-toughness correlation based on Charpy initiation energy', Fracture Mechanics: 13th Conference, ASTM-STP-743, Ed: Roberts R, American Society for Testing and Materials, 207-217.

A20 Priest A H, Charnock W, Stewart A T: 1982, 'The effect of accelerated irradiation on fracture behaviour', Effects of radiation on materials: 11th conference, ASTM-STP-782, Ed: Brager H R, Perrin J S, American Society for Testing and Materials, 475-491.

A21 Witt F J: 1983, 'Relationships between Charpy impact-shelf energies and upper-shelf K_{Ic} values for reactor pressure vessel steels', Int J Pres Ves & Piping, **11**, 47-63.

A22 Begley J A, Logsdon W A: 1971, 'Correlation of fracture toughness and Charpy properties for rotor steels', Westinghouse Research Laboratories Scientific paper 71-1E7-MSLRF-P1, presented at the 5th Nat. Symp. on Fracture Mechanics, Pittsburg, P Cited by Pisarski H G: 1978, The Welding Institute Research Bulletin, **19**, (12), 1978, 362-367, and by Roberts R, Newton C: 1981, Welding Research Council Bulleetin, **265**, 1-18.

A23 Oldfield W, Server, W L: 1984, 'Fracture toughness prediction for pressure vessel steels: the development of a statistically based method', Reference fracture toughness procedures applied to pressure vessel materials, Ed: Mager T R: Presented at the Winter annual meeting of the American Society of Mechanical Engineers, New Orleans, Louisiana, December 9-14 1984, 9-26.

A24 Richardson A K, Server W L, Reuter W G: 1985, 'Adequacy of estimates and variability of fracture-related properties for reactor vessel materials', Int J Pres Ves & Piping, **19**, 299-315.

A25 Girenko V S, Lyndin V P: 1985, 'Relationship between the impact strength and fracture mechanics criteria δ_{Ic} and K_{Ic} of structural steels and welded joints in them', Automatic Welding, September, 13-19.

A26 BSI PD6493:1991: 'Guidance on methods for assessing the acceptability of flaws in fusion welded structures', British Standards Institution, London.

A27 Hartbower C E, Reuter W G, Crimmens P O: 1969, 'Tensile properties and fracture toughness of 6Al-4V titanium', AFML-68-163, Air Force Materials Laboratory, Dayton, OH. Cited by Roberts R, Newton C: 1981, Welding Research Council Bulletin, **265**, 1-18.

A28 Ronald T M F, Hall J A, Pierce C M: 1972, 'Usefulness of precracked Charpy specimens for fracture toughness screening tests of titanium alloys', Metallurgical Transactions, **3**, 813-818. Cited by Roberts et al: 1981, Welding Research Council Bulletin, **265**, 1-18.

A29 Ito T, Tanaka K, Sato M: 1973, 'Study of brittle fracture initiation from surface notch in welded fusion line'. IIW Doc. No. X-704-73.

A30 National Materials Advisory Board: 1976, 'Rapid inexpensive tests for determining fracture toughness', Report No. NMAB-328, National Academy of Sciences. Cited by Roberts et al: 1981, Welding Research Council Bulletin, **265**, 1-18.

A31 Nogata F, Takahashi H, 1986: 'Fracture mechanics evaluation of irradiated embrittlement in reactor vessel steels based on the rate process concept', J of Testing and Evaluation, JTEVA, **14**, (1), 40-48.

A32 Yi L, Xue-Wen T, Nai-Ji L, Xiao-Wei L: 1987, 'Determination of K_{IC} of mild steel by the impact method of testing side-grooved precracked TPB specimens', Eng Frac Mech, **28**, (3), 361-364.

A33 Nageswara Rao B, Acharya A R: 1989, 'Charpy V-notch impact test: a partial alternative to ASTM E399 fracture testing for routine quality control applications', Eng Frac Mech, **32**, (1), 39-42.

A34 Roberts R, Newton C: 1981, 'Interpretive Report on small-scale test correlations with K_{Ic} data'. Welding Research Council Bulletin, **265**, 1-18.

A35 Pisarski H G: 1978, 'A review of correlations relating Charpy energy to K_{Ic}', The Welding Institute Research Bulletin, **19**, (12), 362-367.

A36 Graville B A: 1988, 'Correlations between Charpy properties and the nil-ductility transition temperature', Project 1-1, CSA verification program for the Offshore Structures Code, Graville Associates Inc.

A37 Hertzberg R W: 1983, Deformation and fracture mechanics of engineering materials, 2nd Ed., John Wiley and Sons, New York.

A38 Chirigos J N, Meyer T A: 1978, 'Influence of material properties variations on the assessment of structural integrity of nuclear components', J Test and Eval, **6**, (5), 289-295. Cited by Pisarski H G: 1978, The Welding Institute Research Bulletin, **19**, (12), 362-367.

A39 Irwin G R, Kraft J M, Paris P C, Wells A A: 1967, 'Basic aspects of crack growth and fracture', Naval Research Laboratory Report 6598, Nov 21. Cited by Roberts et al: 1981, Welding Research Bulletin, **265**, 1-18.

A40 Pellini W S: 1968, 'Advances in fracture toughness characterisation procedures and in quantitative interpretations to fracture safe design for structural steels', Naval Research Laboratory Report No. 6713. Cited by Roberts et al, 1981, Welding Council Research Bulletin, **215**, 1-18.

A41 Shoemaker A K, Rolfe S T: 1971, 'The static and dynamic low-temperature crack-toughness performance of seven structural steels', Engineering Fracture Mechanics, **2**, 87-93. Cited by Roberts et al, 1981, Welding Council Research Bulletin, **265**, 1-18.

A42 Server W L: 1979, 'Elastic-plastic fracture, ASTM STP 668, American Society for testing and materials, 493-514. Cited by Norris et al, 1981, ASTM STP 743, 207-217.

A43 Wullaert R A, Oldfield W, Server W L: 1980, 'Reference fracture toughness curves for irradiated pressure vessel steels', J of Eng Mat and Tech, **102**, (1), 101-106.

A44 Oldfield W: 1980, 'Development of fracture toughness reference curves', J of Eng Mat and Tech, **102**, (1), 107-117.

A45 Anil Kumar P V, Nageswara Rao B, Acharya A R: 1990, 'Statistical scatter in fracture toughness of M250 grade maraging steel predicted from Charpy V notch impact test, Eng Frac Mech, **37** (4), 735-738.

A46 Habashi M, Miannay D, Tvrdy M, Galland J: 1986, 'Correlation between apparent toughness K_A and Charpy impact energy in high and low strength steels'. Advances in Fracture Research, 2, (Fracture 84), Ed: Valluri S R, Taplin D M R, Ramn Rao P, Knott J F, Dubey R: Proc 6th Int Conf on Fracture, ICF6, New Delhi, 4-10 Dec 1984, Pergamon Press, 1551-1558.

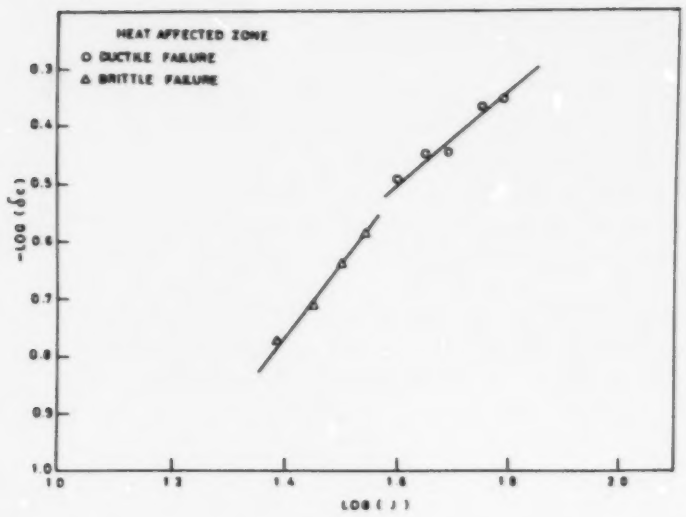

Fig.A.1.1.1 Correlation between critical CTOD and impact energy of HAZ (A1). See correlations [A.1.1] and [A.1.2]

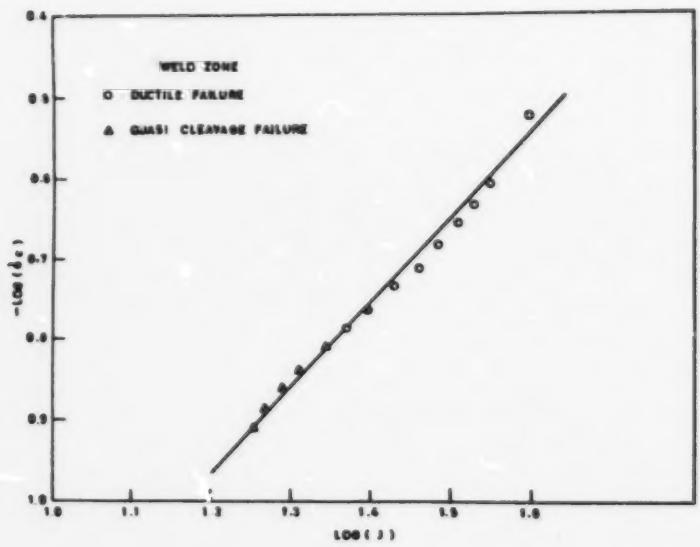

Fig.A.1.1.2 Correlation between critical CTOD and impact energy of WM (A1). Se correlation [A.1.3]

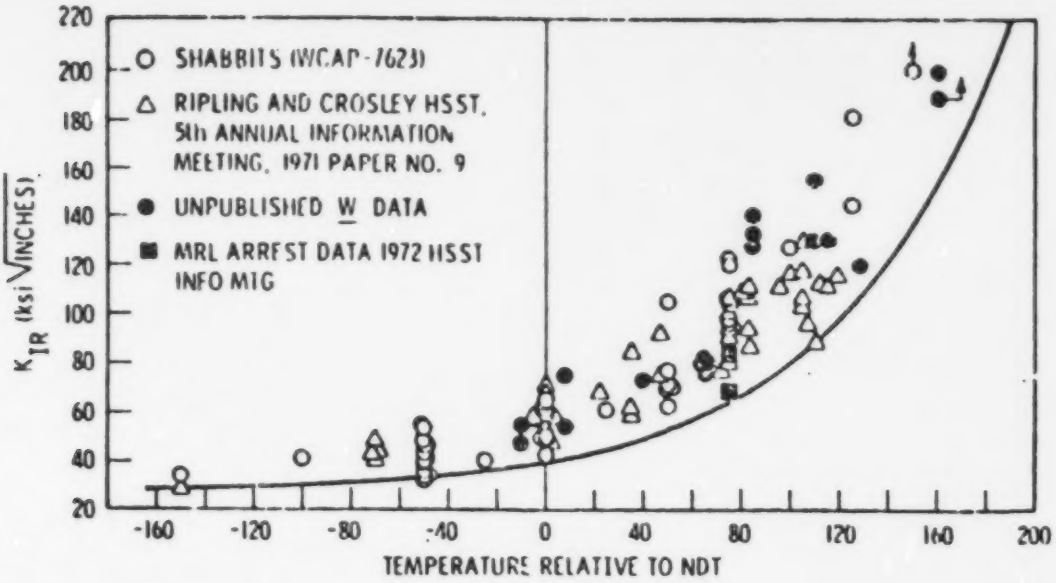
SHABBITS (WCAP-7623)
RIPLING AND CROSLEY HSST, 5th ANNUAL INFORMATION MEETING, 1971 PAPER NO. 9
UNPUBLISHED W DATA
MRL ARREST DATA 1972 HSST INFO MTG
K_{IR} (ksi $\sqrt{INCHES}$)
TEMPERATURE RELATIVE TO NDT

Fig.A.2.2. PVRC correlation (A3)

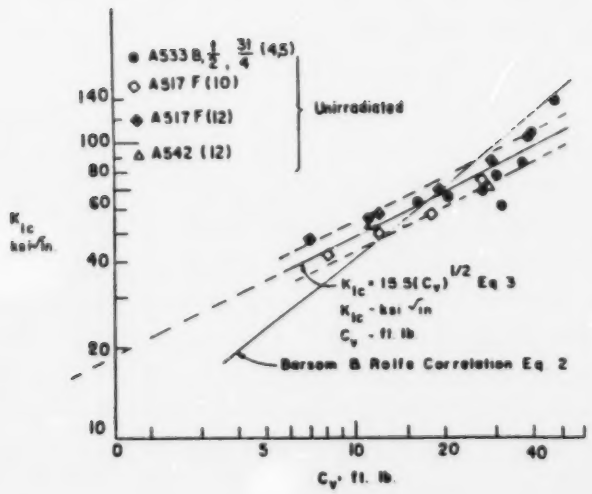

Fig.A.2.3.1 K_{Ic}-Cv correlation for a series of non-irradiated steels (A4). See correlation [A.2.3.1]

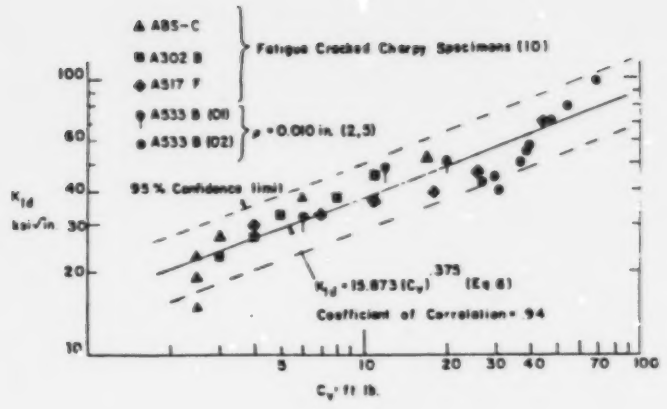

Fig.A.2.3.2 K_{Id}-Cv correlation for a series of non-irradiated steels (A4). See correlation [A.2.3.2]

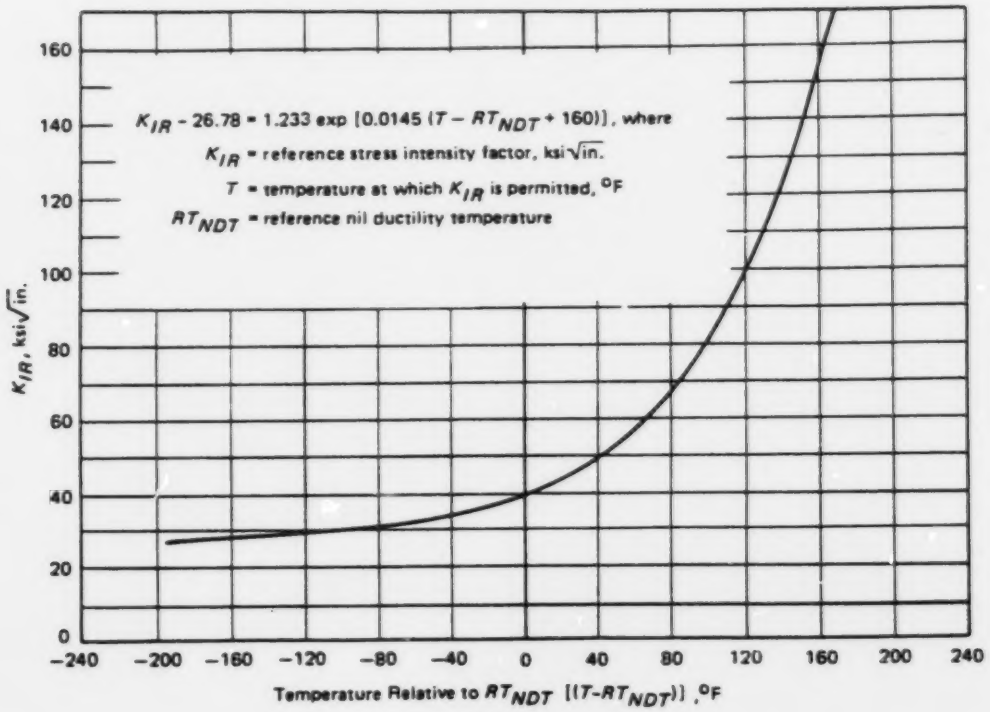
K_{IR} - 26.78 = 1.233 exp [0.0145 ($T - RT_{NDT}$ + 160)], where
K_{IR} = reference stress intensity factor, ksi√in.
T = temperature at which K_{IR} is permitted, °F
RT_{NDT} = reference nil ductility temperature
K_{IR}, ksi√in.
Temperature Relative to RT_{NDT} [(T-RT_{NDT})], °F

Fig.A.2.4 ASME III Appendix G reference fracture toughness curve (A5)

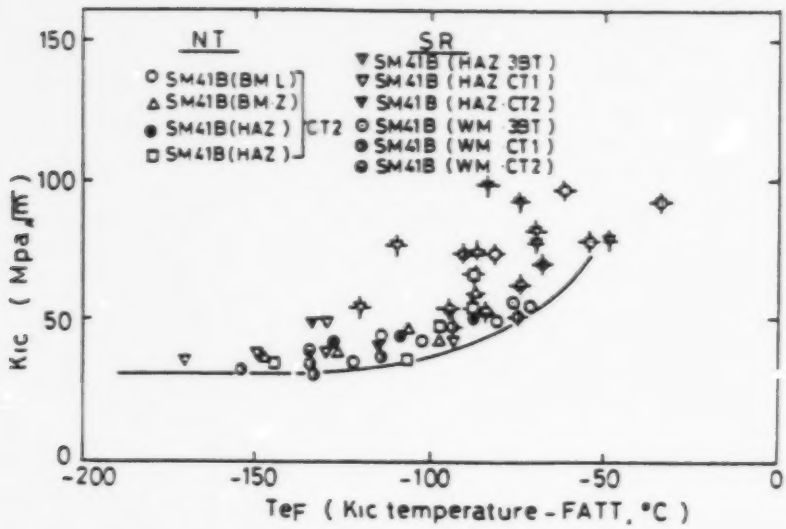

Fig.A.2.5 Correlation [A.2.5.1] of Matsumoto et al (A7)

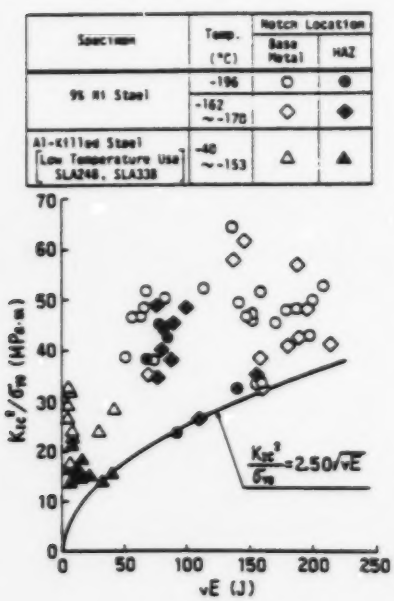

Fig.A.2.6 K_{Ic}-Cv correlation of Imai et al (A8)

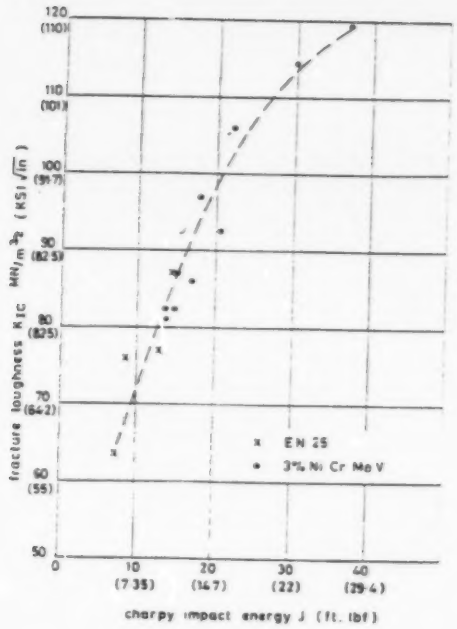

Fig.A.3.1 Logan and Crossland/Thorby and Ferguson correlation (A9)

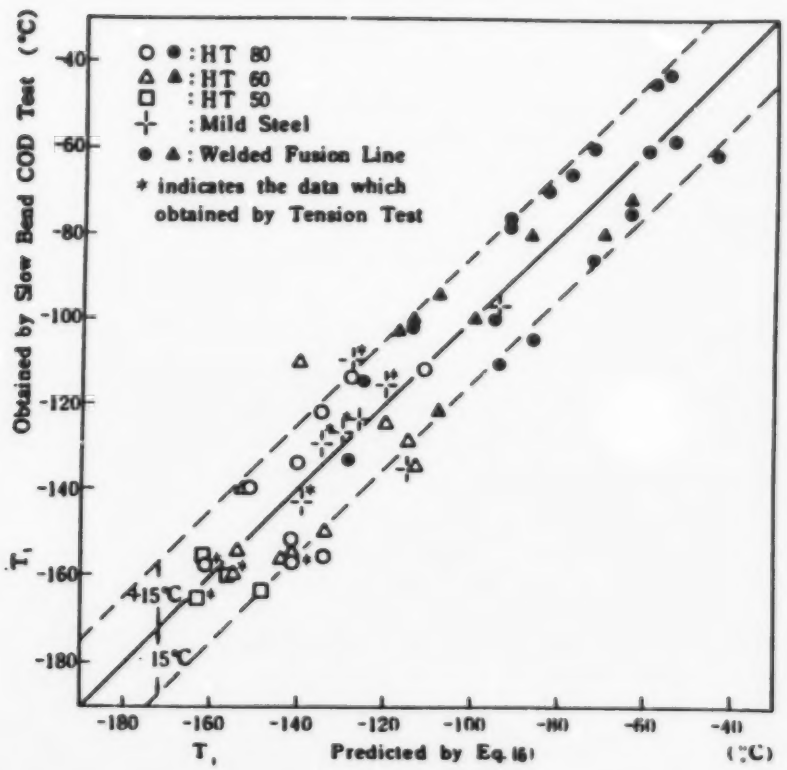

Fig.A.3.2. Accuracy of temperature shift technique of Kanazawa et al (A10). 'Eq.[6]' in this figure is equivalent to Eq.[A.3.2] in this report. 'T_i' references the CTOD temperature transition curve

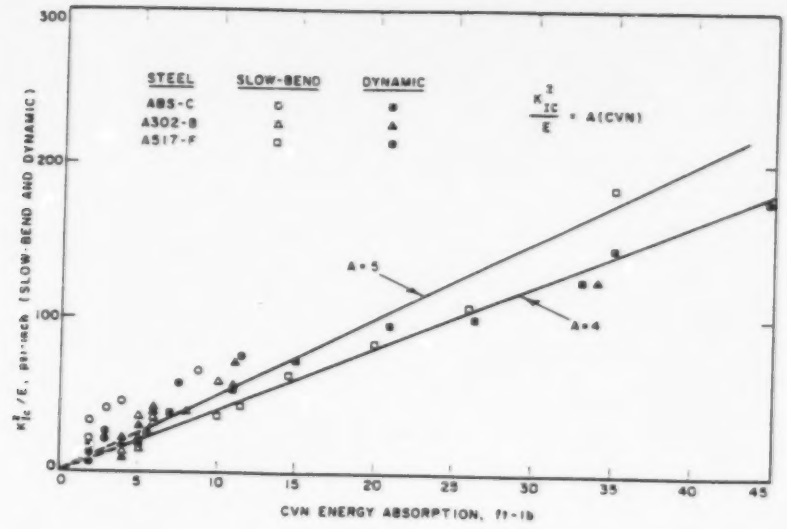

Fig.A.3.3 Barsom correlation (A11). See Eq.[A.3.3.1 to A.3.3.4]

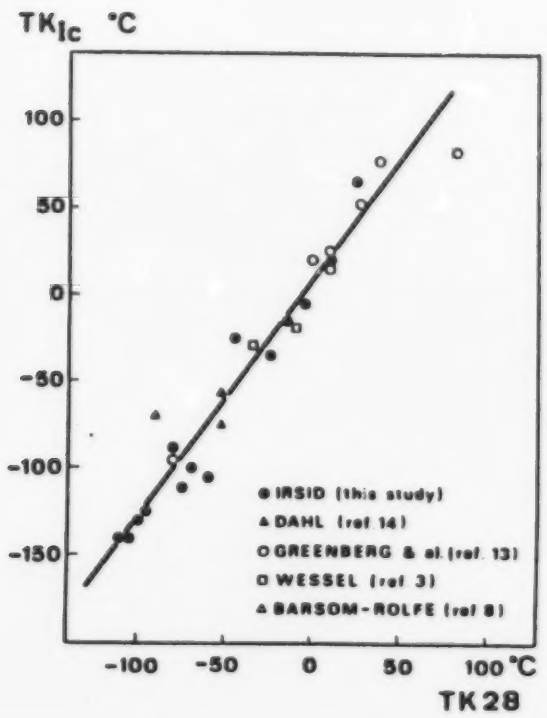

Fig.A.3.4 Marandet and Sanz temperature shift correlation (A12). See Eq.[A.3.4.2].

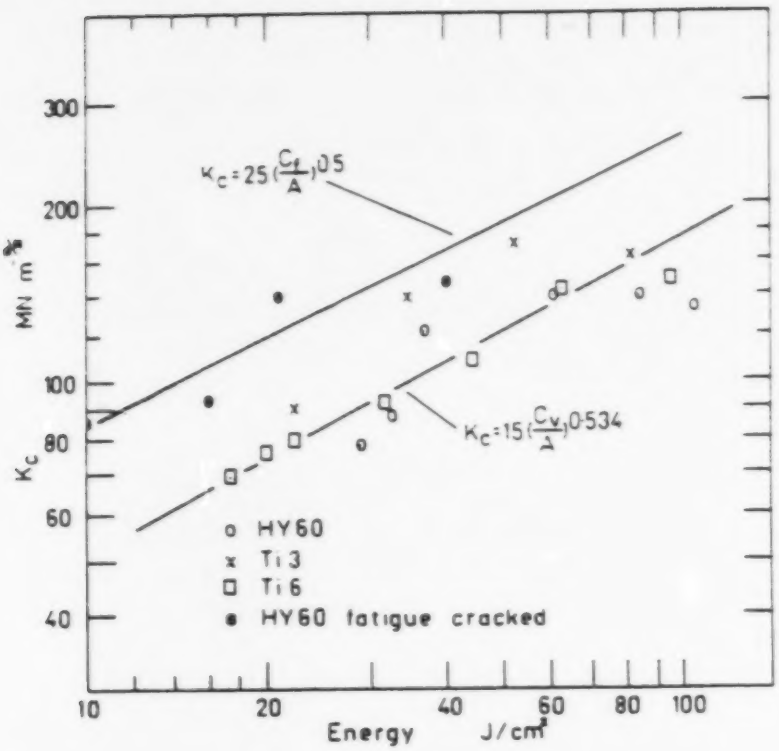

Fig.A.4.1 Thorby and Ferguson correlation (A13)

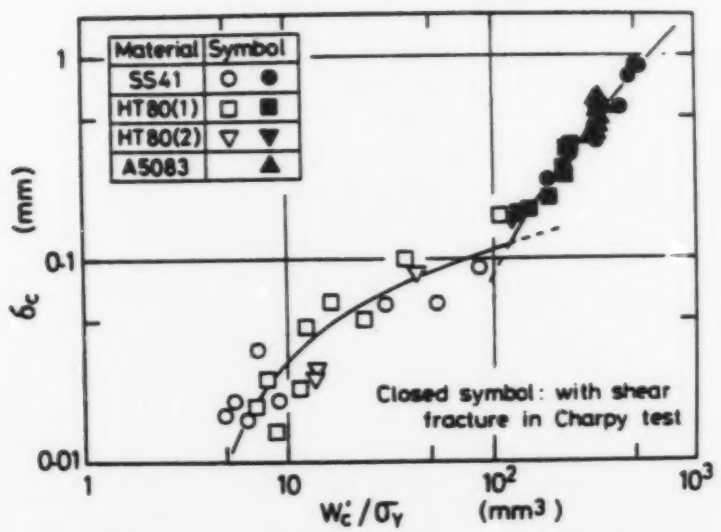

Fig.A.4.2.1 δ_i-Cv correlation [A.4.2.1] of Oda (A14).

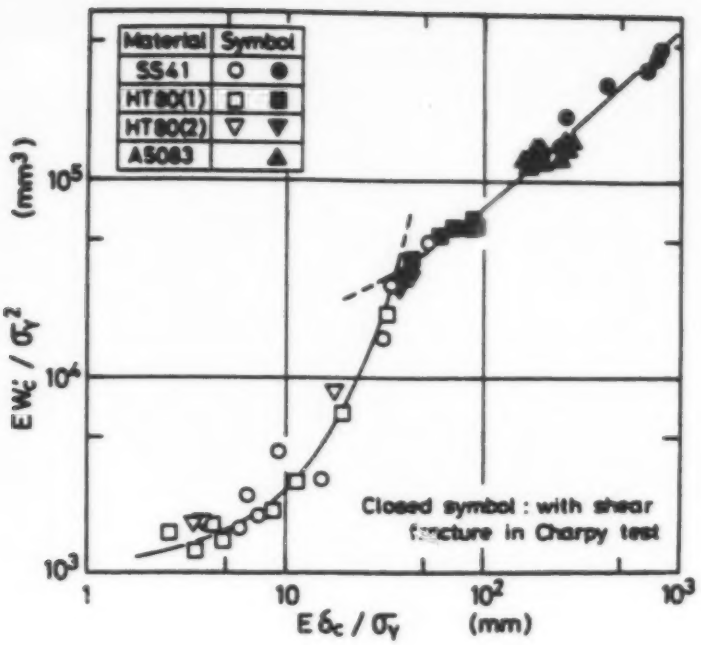

Fig.A.4.2.2 δ_i-Cv correlation [A.4.2.2) of Oda.

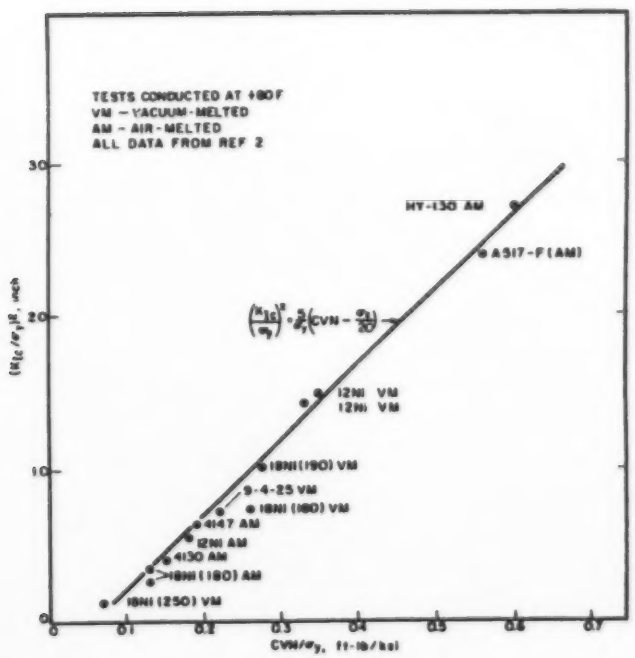

Fig.A.5.1.1 Correlation [A.5.1.1] of Barsom et al (A15)

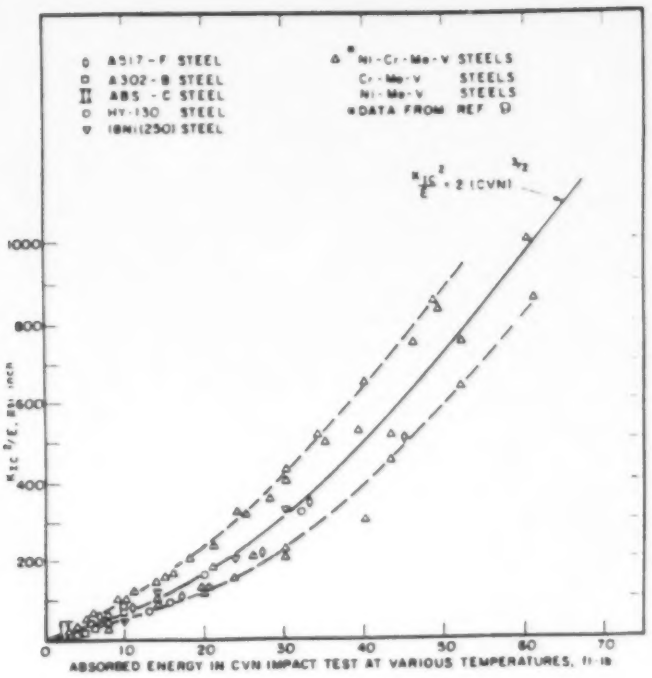

Fig.A.5.1.2 Correlation [A.5.1.2] of Barsom et al (A15)

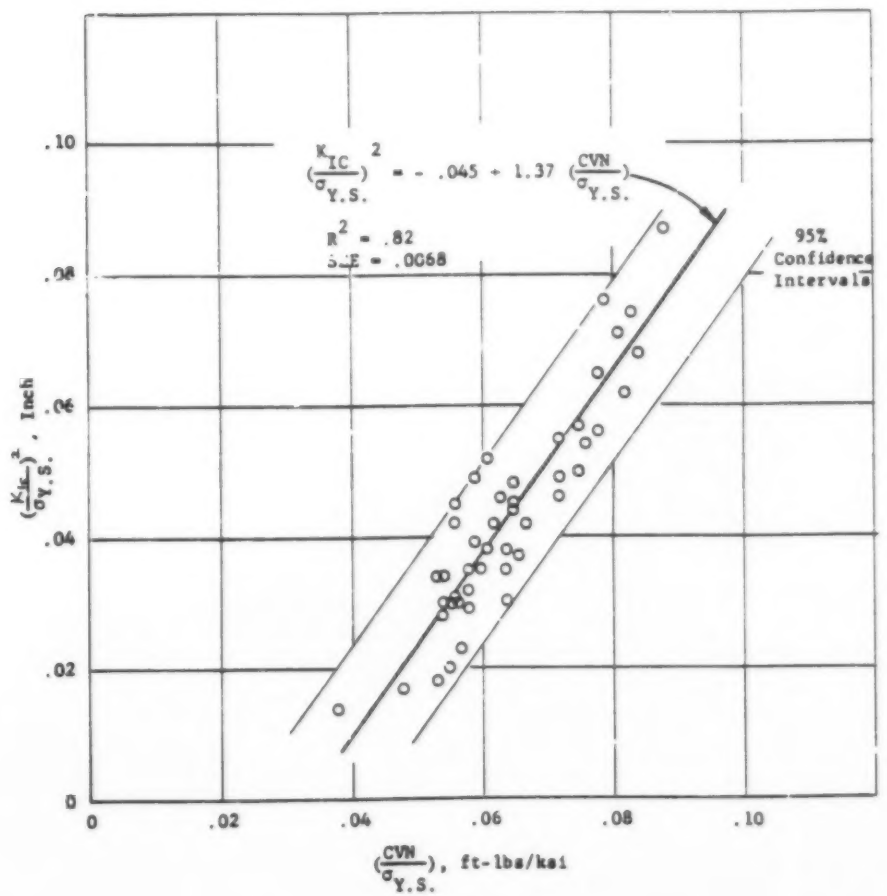

Fig.A.5.2 Ault, Waid and Bertolo correlation (A18)

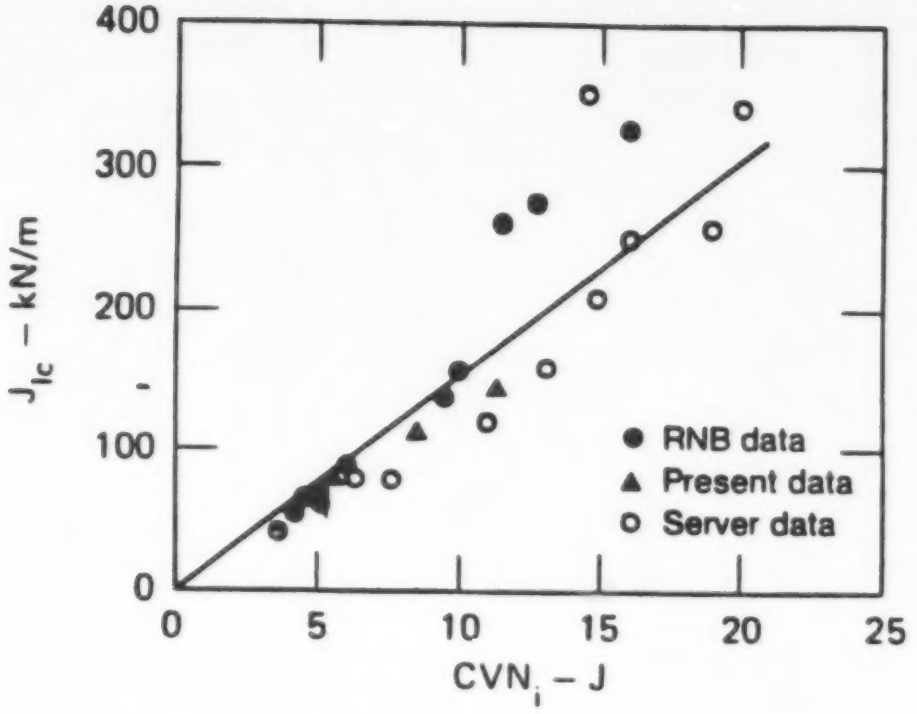

Fig.A.5.3 Correlation [A.5.3.1] of Norris et al (A19)

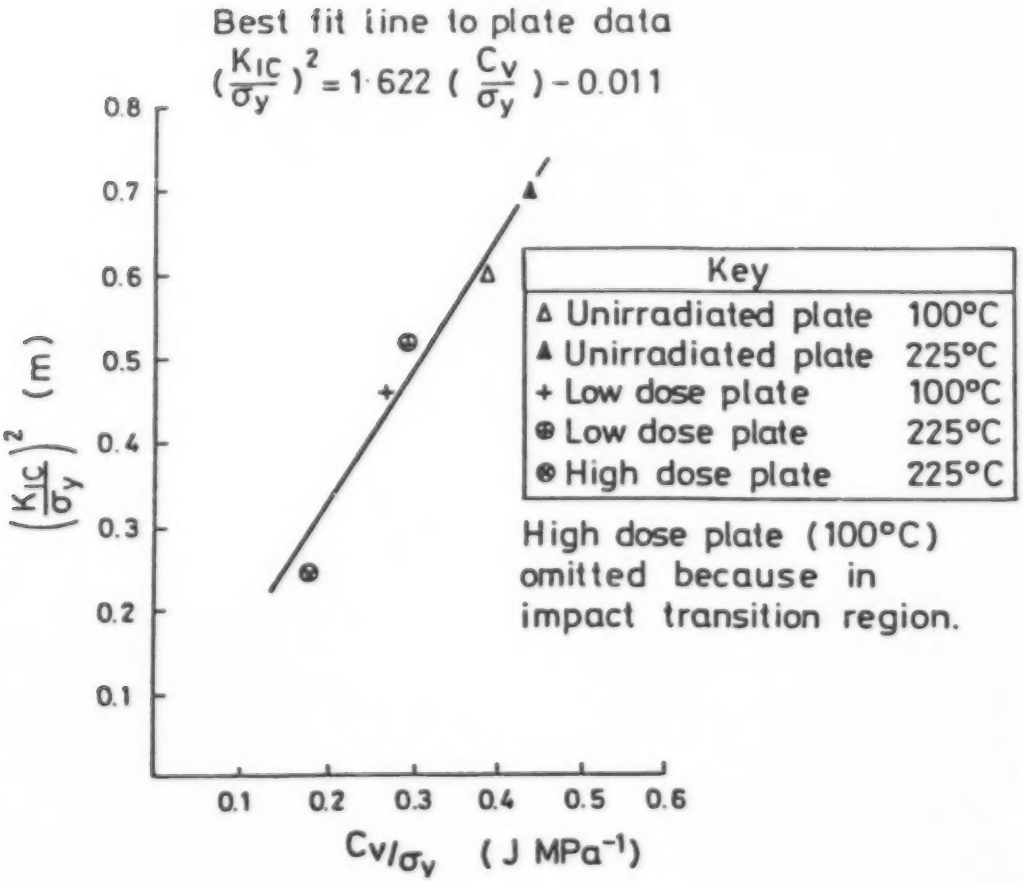

Fig.A.5.4 Correlation [A.5.4.2] of Priest et al (A20)

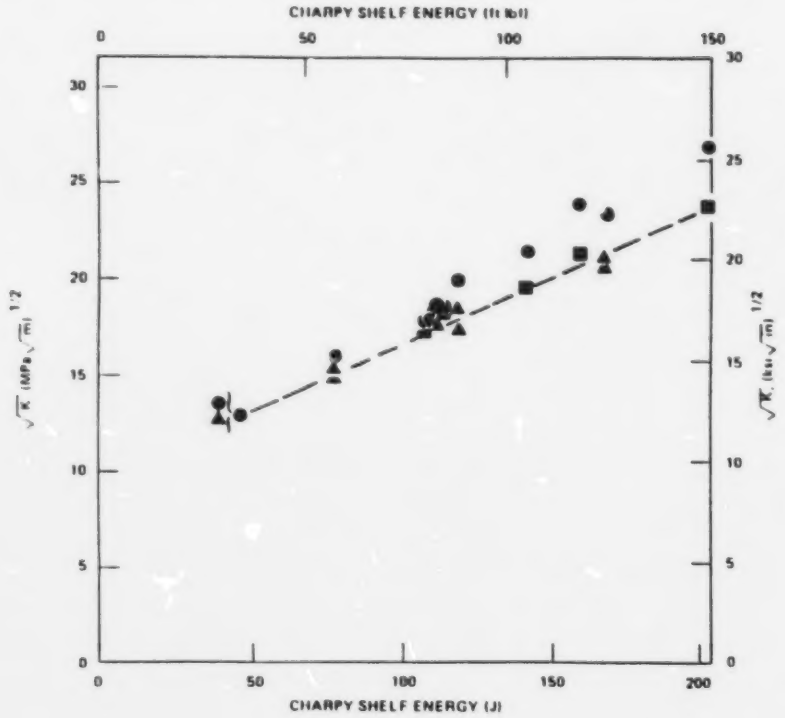

Fig.A.5.5 Correlation [A.5.5.2] of Witt (A21)

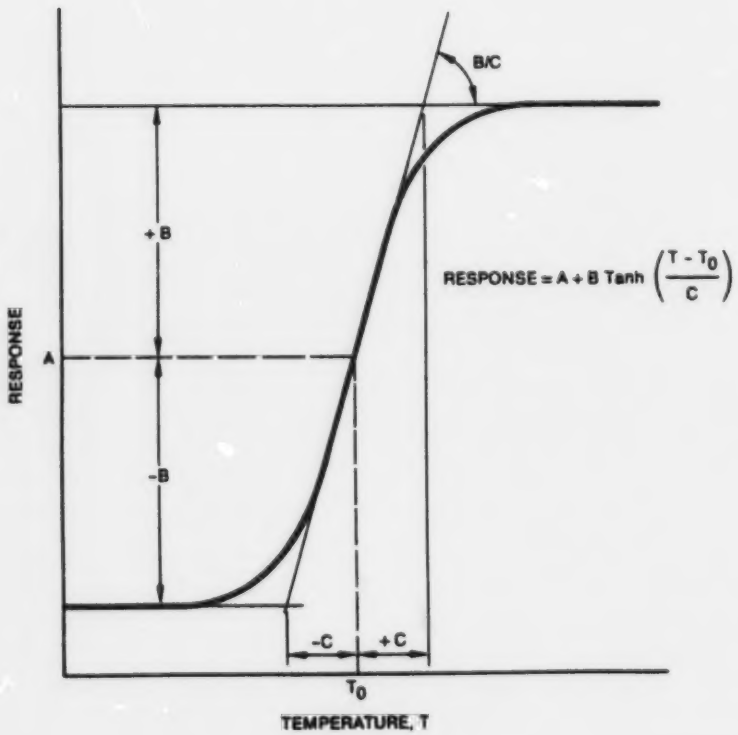

Fig.A.6.2.1 Generalised tanh function of Oldfield et al (A23,A43,A44)

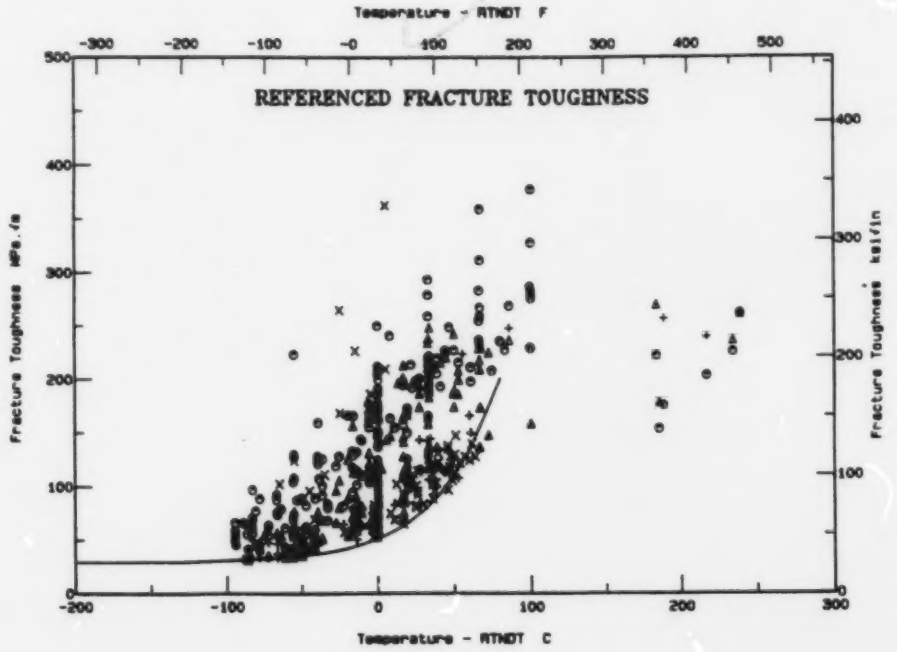

Fig.A.6.2.2 Standard fracture toughness reference curve, Eq.[A.6.2.1] (A23,A43,A44)

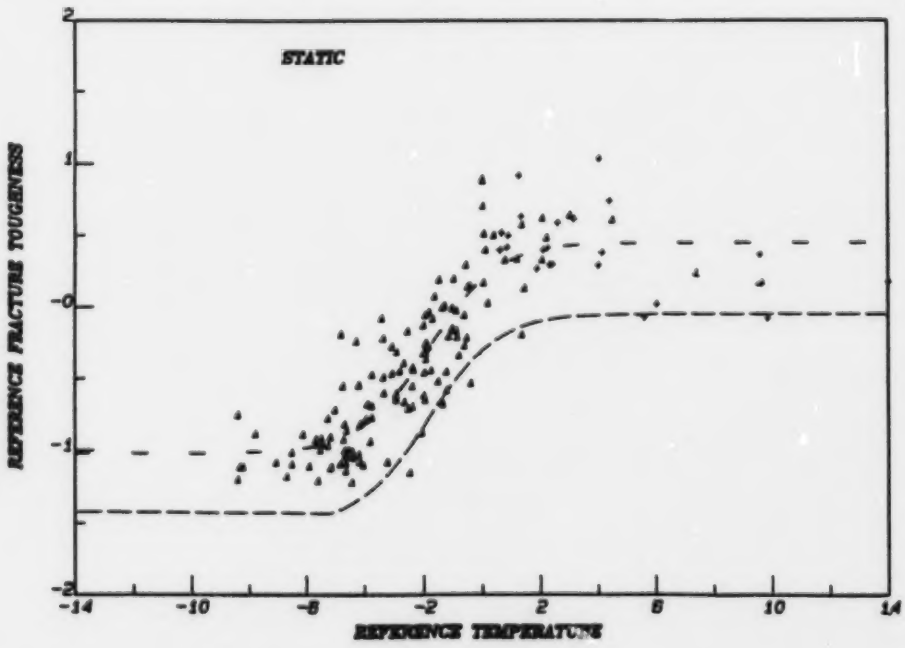

Fig.A.6.2.3 Typical 3-parameter lower-bound tanh function curve (A23,A43,A44)

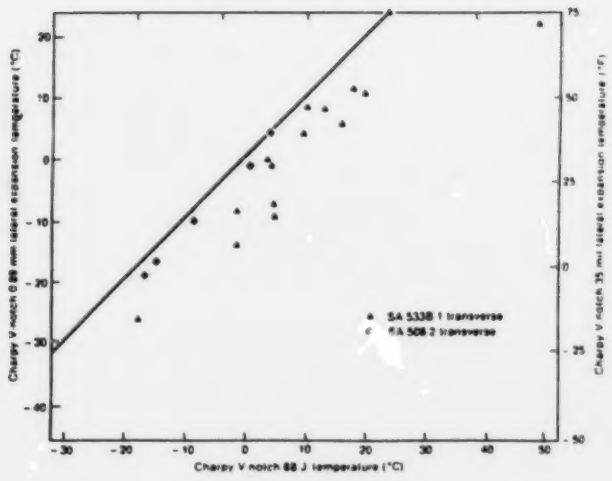

Fig.A.6.3.1 Correlation between 0.89mm lateral expansion and 68J Charpy V notch temperature (A24)

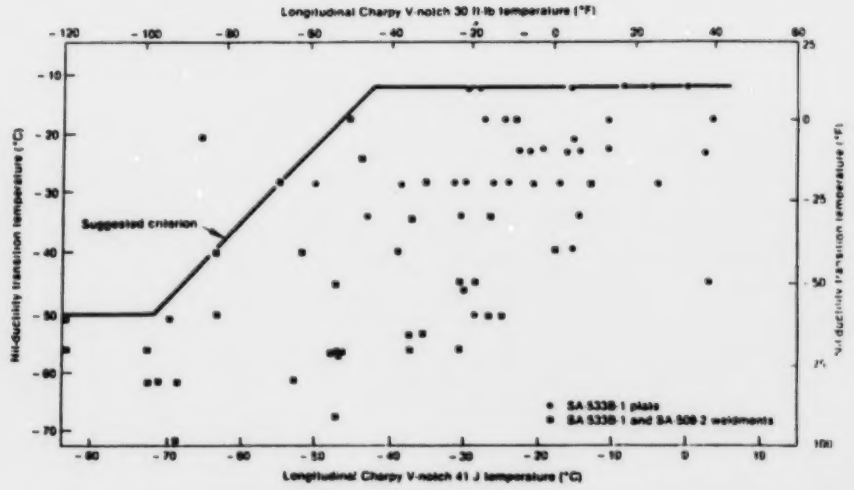
Longitudinal Charpy V-notch 30 ft-lb temperature (°F)
Suggested criterion
SA 533B 1 plate
SA 533B 1 and SA 508 2 weldments
Longitudinal Charpy V-notch 41 J temperature (°C)

Fig.A.6.3.2 Correlation between NDT and Charpy V notch 41J temperature (A24)

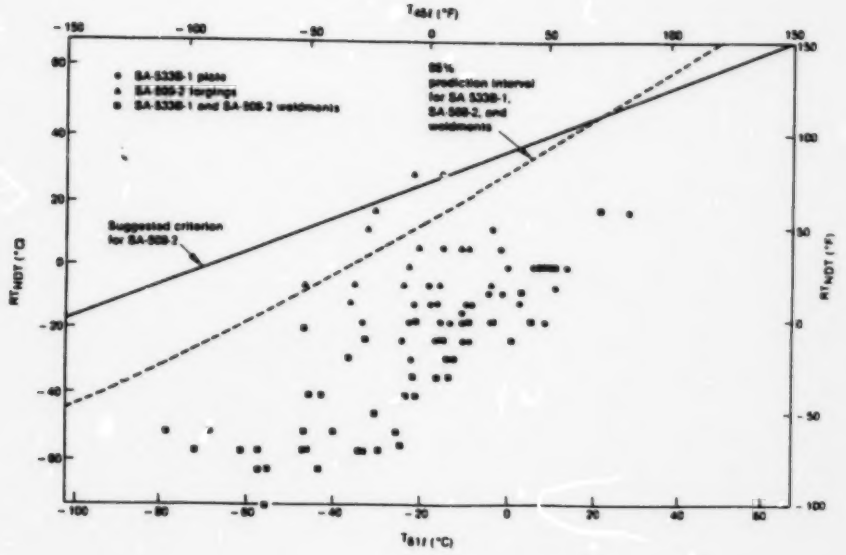

Fig.A.6.3.3 Correlation between RT_{NDT} and Charpy V notch 61J temperature (A24)

experimental values of K_{Ic}: ● — steel not tempered; ○ — tempered at 200°C; △ — the same, 300°C; □ — the same, 400°C; ▲ — the same, 500°C.

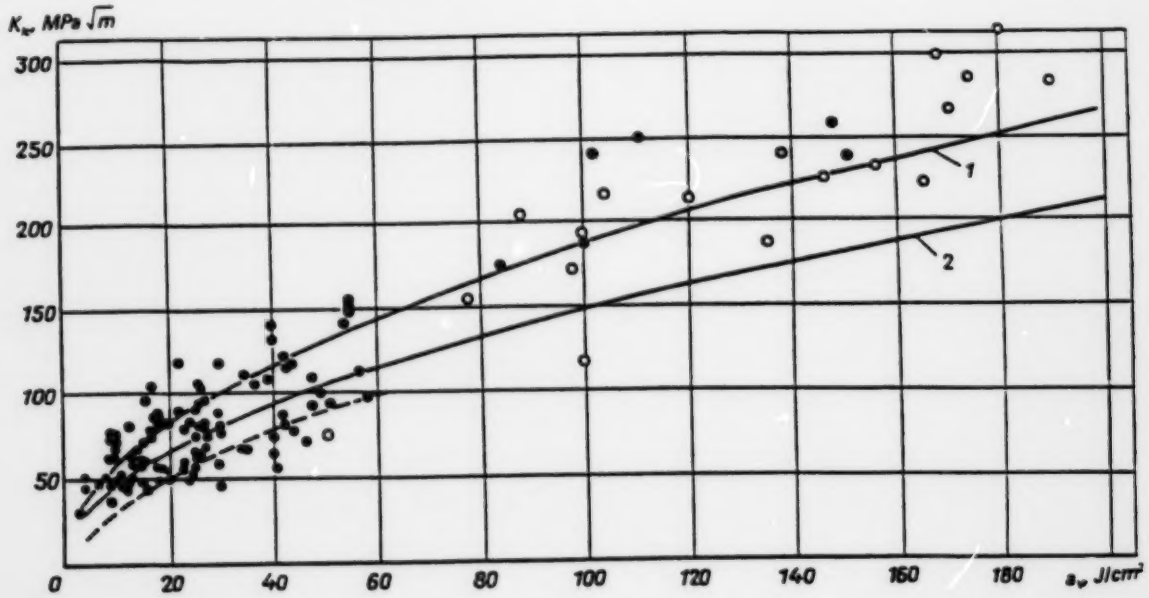

Fig.A.6.4 Correlations [A.6.4.1] to [A.6.4.3] of Girenko et al (A25). The symbol '1' in the figure refers to correlation [A.6.4.1], '2' to [A.6.4.2], while the dotted line represents [A.6.4.3]

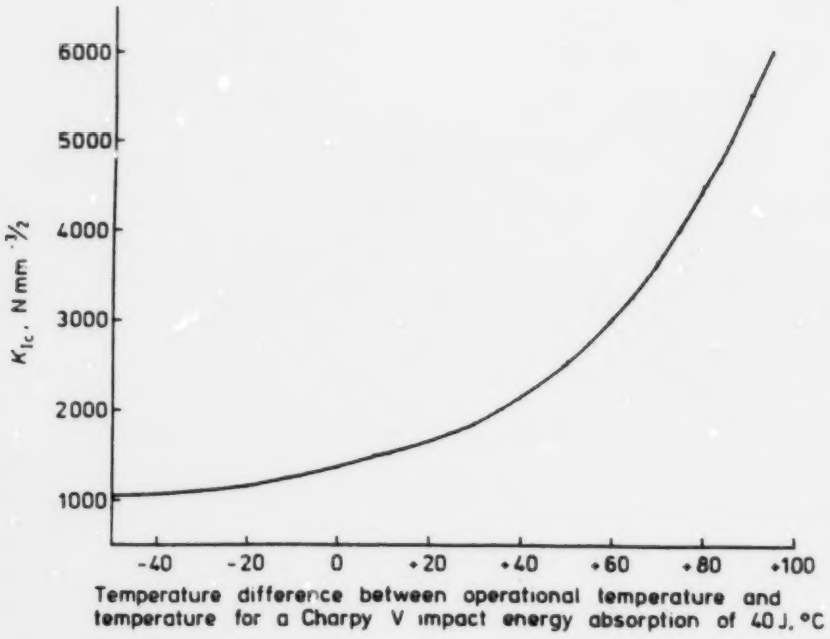

Fig.A.6.5.1 Lower-shelf and transition BSI PD6493 (A26) K_{Ic}-Cv correlation

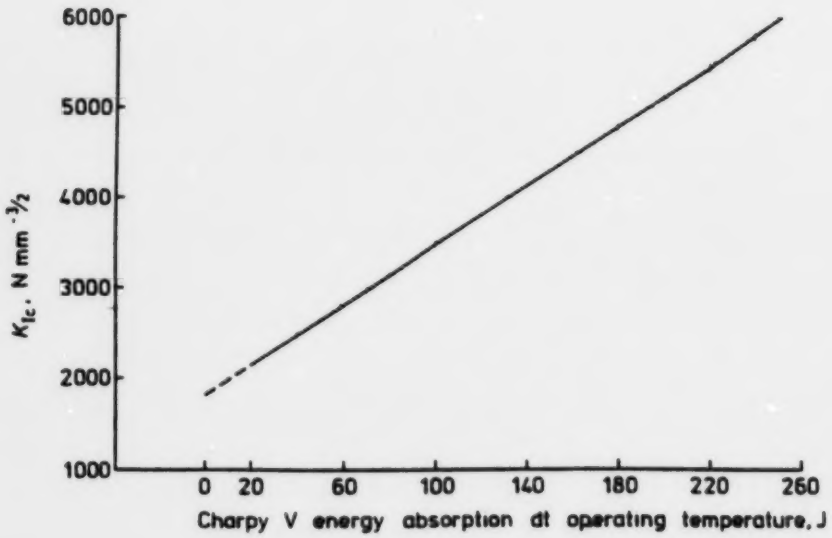

Fig.A.6.5.2 Upper-shelf BSI PD6493 (A26) K_{Ic}Cv correlation

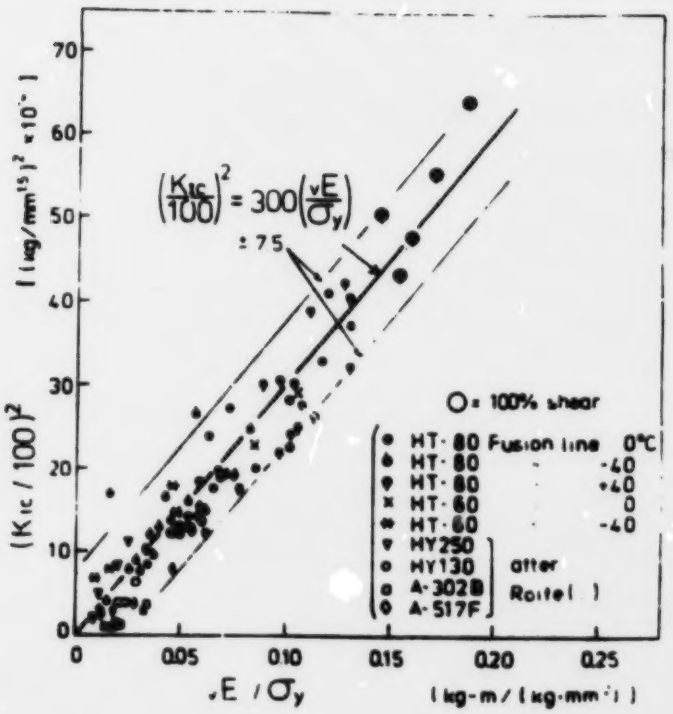

Fig. A.7.3 Ito, Tanaka and Sato correlation (A29)

APPENDIX B

CvK Charpy-toughness correlation
software

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APPENDIX B: CvK CHARPY-TOUGHNESS CORRELATION SOFTWARE

B.1 INTRODUCTION

This Appendix describes in detail the structure of CvK (GSP 5605 Charpy-toughness correlation software), and is intended to act as a user guide.

CvK is a PC-based (IBM compatible) program which provides for efficient display, comparison, validation and use of the correlations which have been investigated in this report. In addition, TWI and user defined data sets may be displayed together with the correlations.

Section B.2 describes the program software, while Section B.3 details the hardware requirements for running CvK. Section B.4 provides installation instructions. Section B.5 describes the structure of CvK and provides details of program control.

B.2 CvK SOFTWARE

The CvK software has been written for Borland Turbo Pascal V6.0 (B1), using the Turbo Vision libraries and Quinn Curtis Graphics library (B2).

B.3 HARDWARE AND SOFTWARE REQUIREMENTS FOR CvK

CvK will run on any IBM or close compatible with the following configuration:

B.3.1 Hardware

Minimum of 640Kb RAM
One 5¼" or one 3½" floppy disk drive (for program installation)
One fixed disk drive (with at least 1Mb of free disk space) or one high density floppy disk drive (3½" or 5¼")
Hercules, CGA, EGA or VGA graphics adaptor and compatible monitor
Parallel printer port and an Epson compatible or HP Laserjet compatible printer, or postscript printer

B.3.2 Software

PC-DOS or MS-DOS operating system version 3.0 or above.

B.4 INSTALLATION INSTRUCTIONS

CvK is supplied on both 3½" and 5¼" floppy disk media. The installation procedure is the same for either disk format, so select the disk type most appropriate and prepare to install the program on your fixed disk drive by carrying out the following instructions:

1. Insert the chosen disk in the relevant drive on your PC.
2. Make this drive the return current drive by typing A: (or B:), followed by pressing the key.
3. Type 'install' and press return key.
4. The screen should clear and you will be asked which directory you want to install to:

A suggested directory name of C:\CvK is supplied and can be accepted by pressing the return key.

If you wish to change the directory name use the backspace key to remove C:\CvK and type in your new directory path (including drive) then press the return key.

The screen should then clear and you will be presented with a list of files which are 'melted' into your specific directory. When the last file has been 'melted' you will be prompted to choose a display adaptor.

There are four choices CGA, Hercules, ECA and VGA. To make a selection use the cursor keys to move the menu bar over the required option and then press the return key to select it.

You will then be asked to select a printer. Highlight the required printer, as above, then press the return key. The program assumes the selected printer is connected to the parallel port, LPT1.

On completion you will be placed into the CvK directory and you can then run the program by typing 'CvK'.

B.4.1 Changing the Configuration

If, after installation, you need to change the screen type or the printer definition this can be achieved by attaching to the CvK directory and typing 'config'.

Select the required options from the menus using the cursor keys and press the return key to accept selections.

CvK will use the new configuration when you next start the program.

B.5 CvK PROGRAM STRUCTURE AND CONTROL

B.5.1 General Program Structure

The global structure of CvK is presented in Fig.B.1. The following sections give an overview of the program features, and detail control commands.

B.5.2 General Program Control

Most of the commands in CvK are menu driven. That is, command options are presented in menus from which options may be selected, using mouse or keyboard control.

B.5.2.1 Mouse control

Mouse control of CvK is similar to other mouse controlled environments, such as MS Windows or Apple Macintosh. The mouse must be installed (using relevant DOS command) before the mouse can be used for CvK control. The on-screen cursor position is controlled by the mouse, and the option selected by using the mouse button. Some functions, such as the help index options, may be selected by 'double clicking' the mouse button (one click to select index option, followed rapidly by another click to view selected help option). Windows of text (help and correlation information screens) may be scrolled using the mouse, by positioning the cursor at the window scroll control bars, and by pressing the mouse button.

B.5.2.2 Keyboard control

The following keyboard commands apply generally:

cursor keys:	controls cursor position within menu
return key:	executes default/selected menu option
space bar:	selects/deselects correlations and materials
tab key: (and shift tab)	moves cursor between sub-menus
esc key:	return to main menu
F1 key:	help facility

Note: most menu functions can be implemented by pressing the key corresponding to the bold letter, e.g. 'q' for Quit.

B.5.3 SI/US Units, English/French Language Options

Execution of the program leads the user to an initial menu screen (after several introductory screens), which permits the system of units (SI or US) and the language (English or French) to be selected (see Fig.B.2). Table B.1 presents the unit definitions which are used in the program. If the French language option is selected then all program functions, help and correlation information screens are displayed in French (except for the text from Appendix A of this report, which is provided as an English text file, and which may be viewed from within the help facility of Cvk).

Control

- use mouse to select unit and language choice, or
- use tab key (and shift tab) to move between unit and language sub-menus,
- use cursor keys to select unit and language sub-menus

- use 'Ok' function or return key to proceed to main menu

B.5.4 Main Menu Options

After the unit system and language have been selected, the main menu is displayed on screen(see Fig.B.3). Main menu options are described in the following sub-sections.

Control

- use mouse to select menu option, and to proceed to chosen option, or
- use tab key (and shift tab) to move between menu options
- use return key to proceed to chosen option

B.5.4.1 PD6493 correlations

Two correlations from BSI PD6493:1991 Appendix B are provided (see Fig.B.4), which are generally considered to be conservative.

Control

- use mouse to select PD6493 correlation, or
- use cursor keys to select PD6493 correlation

- use 'Ok' function or return key to view correlation information and display correlation for use
- use 'Cancel' function or esc key to return to main menu

B.5.4.2 Full correlation options

Published correlations, TWI and user defined data sets are listed, and may be selected for display (see Fig.B.5). The Display Mode is also selected here (see Section B.5.6). Table B.2 lists the published correlations (reviewed in this report), which have been incorporated into the CvK program, together with Appendix A section references.

Control

- use mouse to select/deselect display mode and correlations to be displayed, or
- use cursor and tab keys (and shift tab) to move within and between sub-menus and to select display mode
- use space bar to select/deselect correlations to be displayed

- use 'Ok' function or return key to view correlation information screens and display correlations for use (see Section B.5.6)
- use 'Cancel' function or esc key to return to main menu

B.5.4.3 Generic material search

This option enables the selection of correlations and TWI data sets which include the general material class chosen from the generic material menu (see Fig.B.6). Specific materials in these correlations are automatically high-lighted on the specific material menu (see Section B.5.4.4), for information. More than one generic material may be chosen, in which case the combined set of associated correlations are selected. Once a general material has been selected then the specific material and correlation menus cannot be altered.

Control

- use mouse to select/deselect generic materials, or
- use cursor keys and space bar to select/deselect generic materials

- use 'Ok' function or return key to return to main menu
- use 'Cancel' function or esc key to return to main menu

B.5.4.4 Specific material search

This option enables the selection of correlations and TWI data sets which include the specific material class chosen from the specific material menu (see Fig.B.7). The list of specific materials is derived directly from the data on which the correlations are based. Once a specific material has been selected then the correlation menu cannot be altered.

Control

- use mouse to select/deselect specific materials, or
- use cursor keys and space bar to select/deselect specific materials

- use 'Ok' function or return key to return to main menu
- use 'Cancel' function or esc key to return to main menu

B.5.4.5 User data base

The user data base may be employed to store data sets, together with comments of the user's choice (see Fig.B.8). These data sets are listed on the full correlation menu, together with the published correlations and TWI data sets. User defined data sets may be displayed with other data sets and correlations, if defined in compatible units. The Log-linear Display Mode may be used to fit correlation equations to the user defined data sets (as described in

Section B.5.6.4). The correlation equation may then be used, as described in Sections B.5.6.6 to B.5.6.8.

The user data base consists of five screens:

- user data base menu: permits user to create a new data set, edit and delete an existing data set.
- load file screen: defines data set name. This must take the form of 'USER.n' where n = 1 to 16.
- set up screen: defines axes labels and units, number of data pairs and user comments (these appear on the correlation information screens). Data sets which are in compatible units may be displayed together. ASCII codes may be used to define characters: 'alt-251' for square root sign, and 'alt-253' for the power of 2. The ASCII codes must be typed on the numeric keyboard.
- data entry screen: entry of data pairs into data base.
- display limits: defines range of graphical display for data set (x and y axes).

Control (user data base menu):

- use mouse to select menu option, or
- use tab key (and shift tab) to select menu option
- use return key to proceed to selected option

Control (load file screen):

- type in file name in which data is to be stored, or
- use mouse to select file name from list of existing file names, or
- use tab key (and shift tab) to move between sub-menus
- use cursor keys to select file name from list of existing file names

- use 'Ok' function or return to proceed to next screen
- use 'Cancel' function or esc key to return to user data base menu

Control (set up screen):

- use mouse or tab key (and shift tab) to select line for text input
- type correlation name, axes labels and units, number of data pairs and up to eight lines of user defined comments
- use 'Ok' function or return to proceed to next screen
- use 'Cancel' function or esc key to return to user data base menu

Control (data entry screen):

- use mouse or tab key (and shift tab) to select line and column for data input
- type in data pairs

- use 'Ok' function or return to proceed to next screen
- use 'Cancel' function or esc key to return to user data base menu

Control (display limits):

- use mouse or tab key (and shift tab) to select line for display limit values
- type in display limit values

- use 'Ok' function or return to proceed to next screen
- use 'Cancel' function or esc key to return to user data base menu.

B.5.5 Help Facility

Help is available from all screens within CvK. An index is displayed, from which the relevant help text may be selected (see Fig.B.9). The text from Appendix A of this report (detailed summary of all correlations reviewed) is provided as a help option (in English only).

Control

- use F1 key to view help index

- use mouse to select help subject
- double click mouse button to view selected help
- use scroll control bars to scroll text, or

- use tab key (and shift tab) to select help subject
- use return key to view selected help
- use cursor keys to scroll text

- use 'Index' function to return to help index
- use 'Cancel' function or esc key to return to CvK

B.5.6 Display Screens

CvK is based around three graphical display modes: Primary Display, Log-linear Display and Comparison Display. These display screens facilitate effective application of the correlations and data sets. Comparisons can be made, and correlations validated. The display modes are selected from the full correlation menu (see Section B.5.4.2). Each display screen has several components (see Fig.B.10):

- graph, for displaying correlations and data sets
- key, for identifying displayed correlations and data sets
- control box, for display of 'active' correlation, 'shift', 'use' and curve fitting parameters (see Sections B.5.6.4 and B.5.6.6 to B.5.6.8)
- work areas, for application of 'use' and 'shift' functions (see Sections B.5.6.6 and B.5.6.7).

B.5.6.1 Correlation information screens

Information on each selected correlation and data set is displayed in sequence, before the correlations can be displayed. This facility enables the user to assess the applicability of the correlations and data sets. Information which is displayed includes:

- the correlation equation
- display units
- materials
- yield strength range
- Charpy energy range
- temperature range
- thickness range
- source and quality of data
- Appendix A section reference
- information of the applicability of the correlation or data set (including weldments)

See Fig.B.11 for an example of a correlation information screen. Correlation information can be printed using the 'print' command (see Section B.5.6.10), which is available from the display screens (see Section B.5.6).

Control

- use mouse or cursor keys to scroll text

- use 'Ok' function or return key to clear current information screen
- use 'Cancel' function or esc key to return to main menu

B.5.6.2 Display units

Once the correlation information screens have been viewed, the display units must be chosen from the menu provided (see Fig.B.12). Only correlations and data sets which are expressed in compatible units may be displayed together. The units in which a correlation may be displayed is limited by the form of the data which is available in the literature (or defined by TWI or the user). Table B.3 lists the correlation and TWI display units, together with the associated variables.

Control

- use mouse to select display units, or
- use cursor keys to select display units

- use 'Ok' function or return key to display correlations
- use 'Cancel' function or esc key to return to main menu

B.5.6.3 Primary display mode

Correlations selected from the correlation menu, together with the data upon which they are based (if available), are plotted in the Primary Display Mode (see Fig.B.13). TWI and user defined data sets may also be displayed, provided the display units are compatible.

B.5.6.4. Log-linear display mode

Correlation data selected from the correlation menu are plotted on log-log axes in the Log-linear Display Mode (see Fig.B.14). TWI and user defined data sets may also be displayed, provided the display units are compatible. A best fit equation of the form $y = ax^b$ ($\log(y) = \log(a) + b \log(x)$) is fitted to each displayed data set by linear regression analysis. The constants 'log(a)' and 'b', and the correlation coefficient 'r' are evaluated for the active data set (see section B.5.6.6 for 'active' command). A best fit linear equation is also fitted to the combined set of displayed data.

B.5.6.5 Comparison display mode

Correlation data selected from the correlation menu are plotted in the Comparison Display Mode (see Fig.B.15). TWI and user defined data sets may also be displayed, provided the display units are compatible. For each pair of data associated with each displayed data set, the actual toughness is plotted against the predicted toughness (predicted using the active correlation equation). In this way, using a conservative correlation equation will result in most data points lying below the active correlation line, defined by K(actual) = K(predicted). If no correlation is available for a set of data, then the best fit equation of the form $y = ax^b$ is used (see Section B.5.6.4).

B.5.6.6 Active command

The 'Active' command may be employed to select which correlation or data set is to be active for use (see Sections B.5.6.7 and B.5.6.8).

Control

- use 'a' key to select active correlation. Several key strokes may be required to select desired correlation.

B.5.6.7 Shift command

The 'Shift' command may be employed to apply a shift to the active correlation equation. In the Primary and Comparison Display Modes the shift is applied in terms of the units corresponding to the vertical axis of the display graph. Algebraically the shift operation corresponds to modifying the (generalised) correlation equation thus: $y = f(x) + shift$. In the Log-linear Display Mode the shift is applied in terms of plus or minus 1 or 2 standard deviations. Algebraically this corresponds to $y = acx^b$, where $c = 10^{shift}$. The shift is reset to zero if a different correlation or data set is activated, or if the user quits from the current display mode.

Control

- use 's' key to apply shift to active correlation, and enter the value of the applied shift as requested.

B.5.6.8 Use command

The 'Use' command may be employed to use the active correlation to predict fracture toughness from a chosen value of the Charpy parameter. The active correlation is used, together with any shift which has been applied. The user is then asked for the input data associated with the active correlation equation.

Control

- use 'u' key to apply active correlation, and enter the appropriate values of the relevant parameters, as requested.

B.5.6.9 Quit command

The 'Quit' command quits from the display screen to the display units screen (see Section B.5.6.2). If only one type of display units is associated with the selected correlations and data sets, then the 'Quit' command will quit to the main menu.

Control

- use 'q' key to quit from display screen

B.5.6.10 Print command

The 'Print' command may be used to produce a hard copy summary for the CvK consultation, including correlation equation (with shift), user defined text (project title and number, user name, date, comments, etc), displayed graph, results of correlation prediction, as well as information on the active correlation or data set (from the correlation information screen, described in Section B.5.5.1).

Control

- use 'p' key to print summary of consultation and/or information on active correlation
- use mouse or tab key (and shift tab) to select line for text input
- type user name, date, project details and comments, as appropriate

B.5.7 TWI Data Sets

TWI data sets have been provided for a range of materials (listed in Table B.4). These data are intended to permit validation of published correlations. Correlation equations may be fitted to the TWI data using the Log-linear Display Mode (as described in Section B.5.6.4). The correlation equation may then be used as described in Sections B.5.6.6 to B.5.6.8). Details of the TWI data are presented in the relevant correlation information screens (see Section B.5.6.1), which may be viewed prior to display.

B.5.8. Tabulated Correlation and TWI Data

The data associated with the published correlations and TWI data sets are stored in read-only files, in SI units. See Table B.5 for list of file names.

B.6 REFERENCES

B1 Borland Turbo Pascal V6.0, Borland International, 1990.

B2 Science and Engineering Tools for Turbo Pascal, Quinn Curtis, 1991.

Table B.1 SI and US units used in CvK program

Parameter	Symbol	SI unit	US unit
Charpy impact engery	Cv	J	ft.lb
Fracture toughness	K	MPa√m	ksi√in
CTOD toughness	δ	mm	in
J-integral toughness	J	N/mm	lbf/in
Temperature	T	°C	°F
Yield strength	σ_y	MPa	ksi

RTNDT, FATT, TF, ΔT, T(40J), etc. are temperature parameters (reference temperatures and temperature shifts). These parameters are defined in the correlation information screens.

Table B2 Published correlations which have been included in CvK program

CvK name	Appendix A reference
ASME/PVRC	A.2.2, A.2.4
Ault	A.5.2
Barsom-1	A.5.1
Barsom-2	A.5.1
Barsom-3	A.3.3
Chaudhuri-1	A.1.1
Chaudhuri-2	A.1.1
Chaudhuri-3	A.1.1
Girenko	A.6.4
Imai	A.2.6
Ito	A.7.3
Logan	A.3.1
Marandet	A.3.4
Matsumoto	A.2.5
Norris	A.5.3
Oda-1	A.4.2
Oda-1	A.4.2
PD6493-1	A.6.5
PD6493-2	A.6.5
Priest-1	A.5.4
Priest-2	A.5.4
Sailors	A.2.3
Thorby	A.4.1
Witt-1	A.5.5
Witt-2	A.5.5

Table B.3 Display unit definitions

SI display unit	US display unit	Parameter symbol
J	ft.lb	Cv
MPa√m	ksi√in	K
mm	in	δ
N/mm	lbf/in	J
°C	°F	T
MPa	ksi	σ_y
J/MPa	ft.lb/ksi	Cv/σ_y
√mm	√in	K/σ_y
MPa.m	ksi.in	K^2/σ_y

Table B.4 TWI data sets

Correlation name	Material	Toughness parameters
TWI-PV1(K)	9% Ni A553 pressure vessel steel	Cv, Kc
TWI-PV2(K)	Nuclear pressure vessel steels (A508, A533B)	Cv, Kc
TWI-PV3(K)	BS 1501 pressure vessel steels	Cv, Kc
TWI-PV4(K)	A204 pressure vessel steel	Cv, Kc
TWI-PL(K)	API 5L pipeline steels	Cv, Kc
TWI-ST(K)	BS 4360 offshore strutural steels	Cv, Kc
TWI-SH1(K)	Lloyd's ship steel (high strain rate)	Cv, Kc
TWI-SH2(K)	LLoyd's ship steel (modern strain rate)	Cv, Kc
TWI-SH3(K)	LLoyd's ship steel (standard strain rate)	Cv, Kc
TWI-PP(δ)	Parent plate, various steels	Cv, CTOD
TWI-WM(δ)	Weld metal, various steels	Cv, CTOD
TWI-HAZ(δ)	HAZs, various steels	Cv, CTOD

Table B.5 Data file names

Correlation name	File name
ASME/PVRC	Info.1
Ault	Info.2
Barsom-1	Info.3
Barsom-2	Info.4
Barsom-3	Info.5
Chaudhuri-1	Info.6
Chaudhuri-2	Info.7
Chaudhuri-3	Info.8
Girenko	Info.9
Imai	Info.10
Ito	Info.11
Logan	Info.12
Marandet	Info.13
Matsumoto	Info.14
Norris	Info.15
Oda-1	Info.16
Oda-2	Info.17
PD6493-1	Info.18
PD6493-2	Info.19
Priest-1	Info.20
Priest-2	Info.21
Sailors	Info.22
Thorby	Info.23
Witt-1	Info.24
Witt-2	Info.25
TWI-PV1(K)	Twinfo.1
TWI-PV2(K)	Twinfo.2
TWI-PV3(K)	Twinfo.3
TWI-PV4(K)	Twinfo.4
TWI-PL(K)	Twinfo.5
TWI-ST(K)	Twinfo.6
TWI-SH1(K)	Twinfo.7
TWI-SH2(K)	Twinfo.8
TWI-SH3(K)	Twinfo.9
TWI-PP(δ)	Twinfo.10
TWI-WM(δ)	Twinfo.11
TWI-HAZ(δ)	Twinfo.12

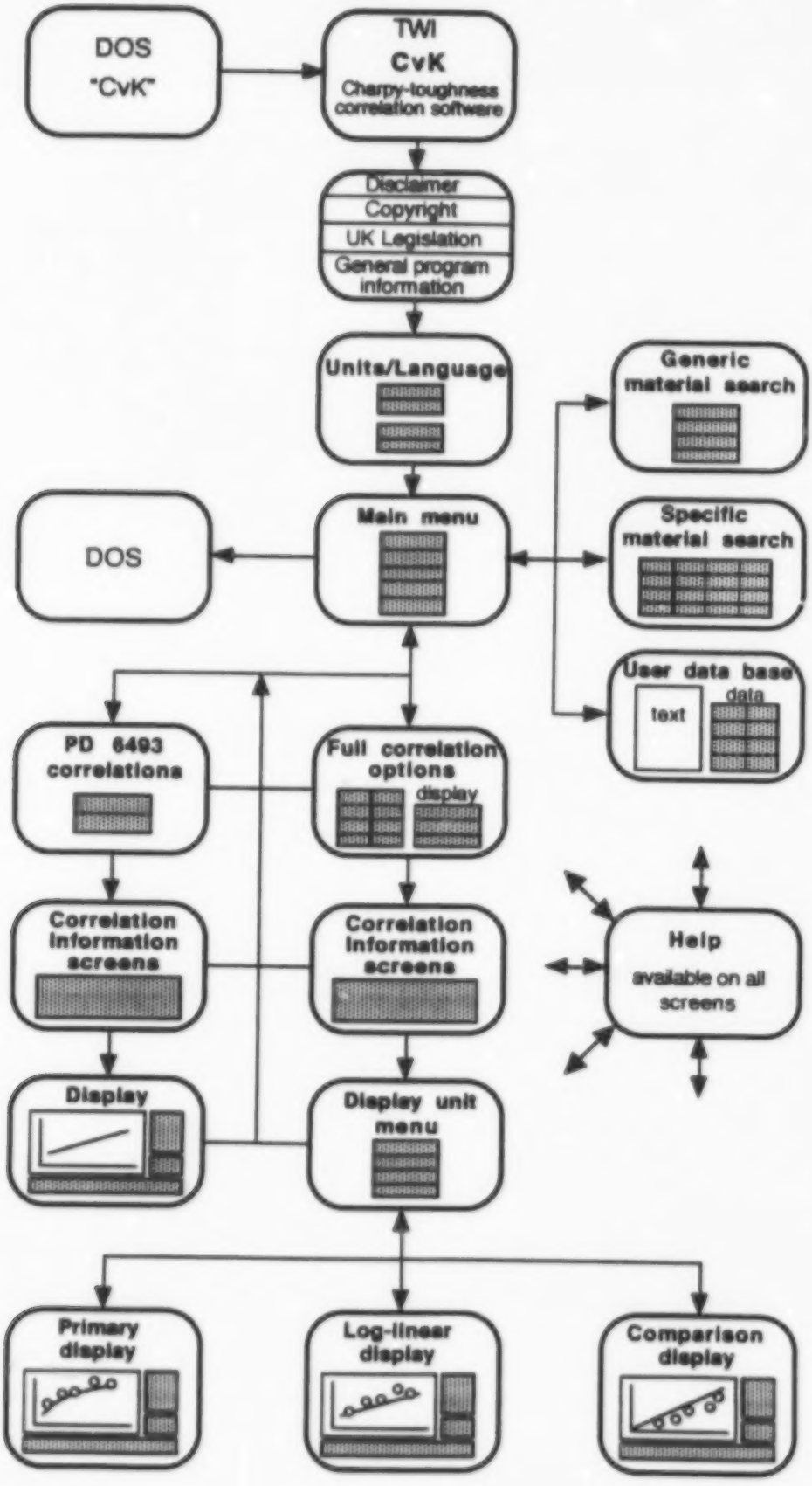

Fig.B.1 Global structure of CvK

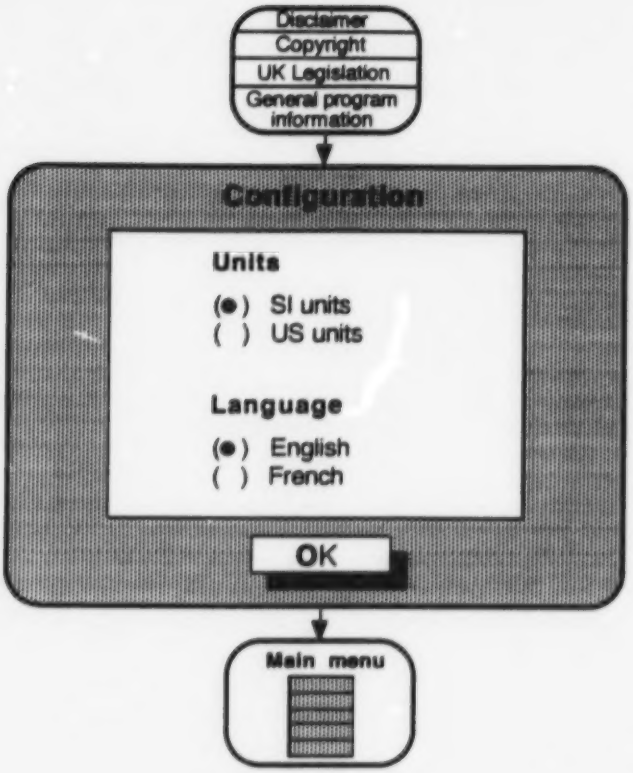

Fig.B.2 SI/US units, English/French language options

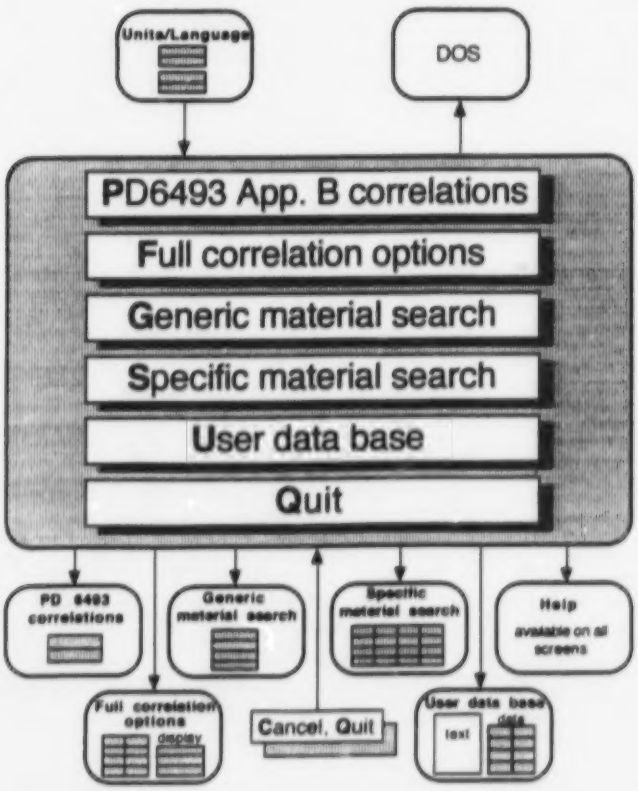

Fig.B.3 Main menu options

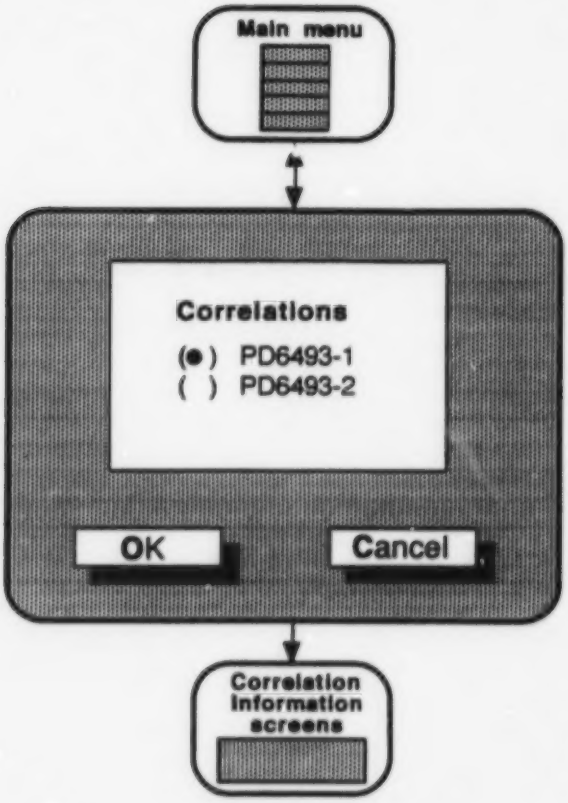

Fig.B.4 PD6493 App. B correlation options

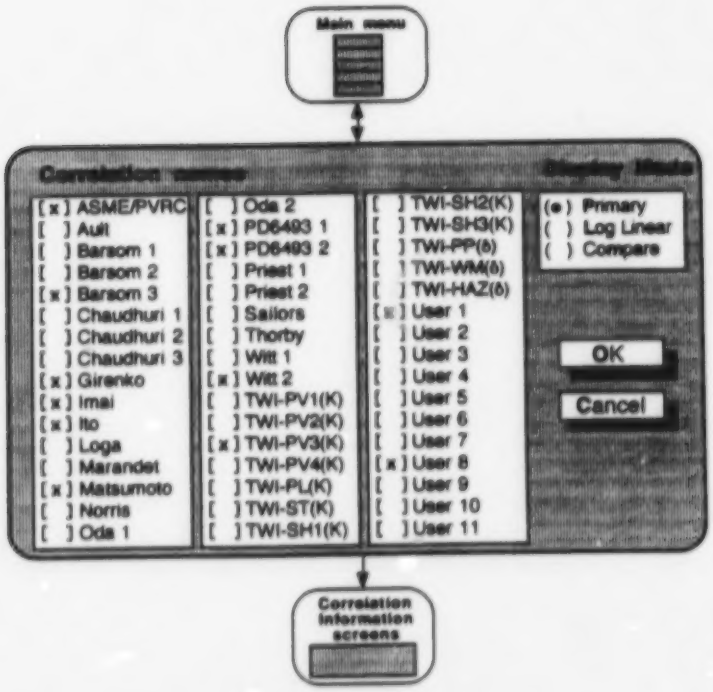

Fig.B.5 Full correlation menu

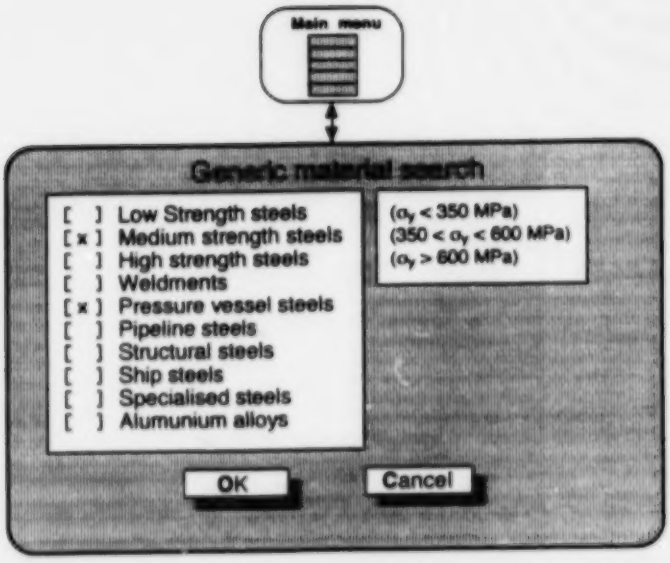

Fig.B.6 Generic material search menu

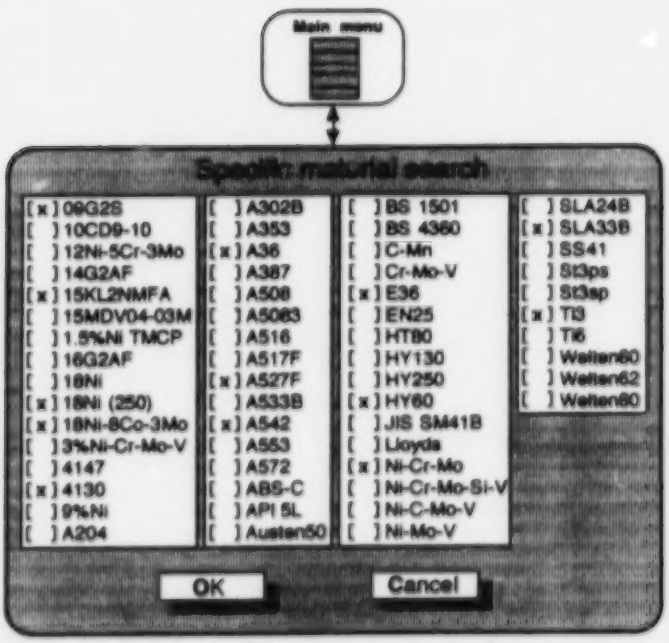

Fig.B.7 Specific material search menu

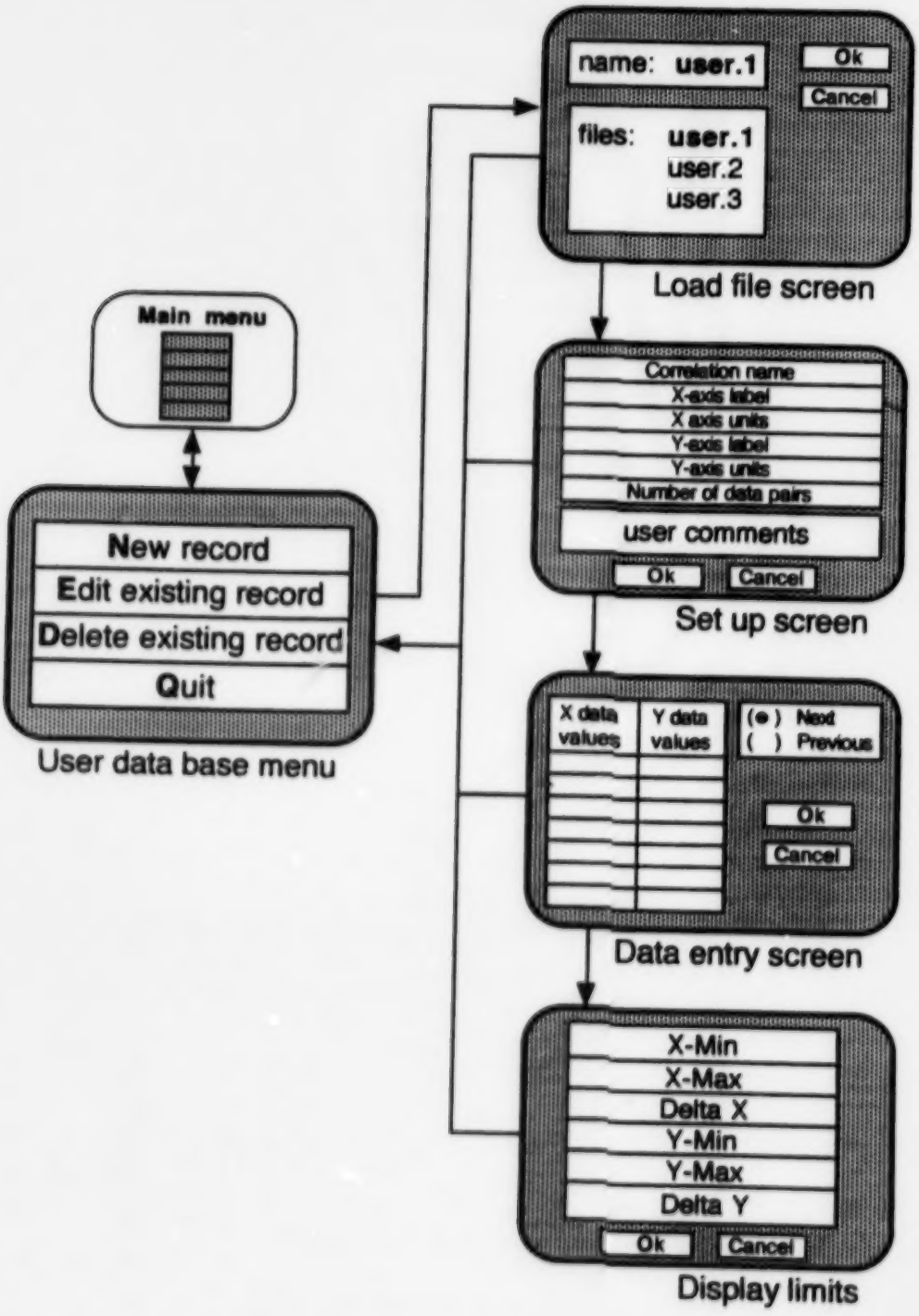

Fig.B.8 User data base

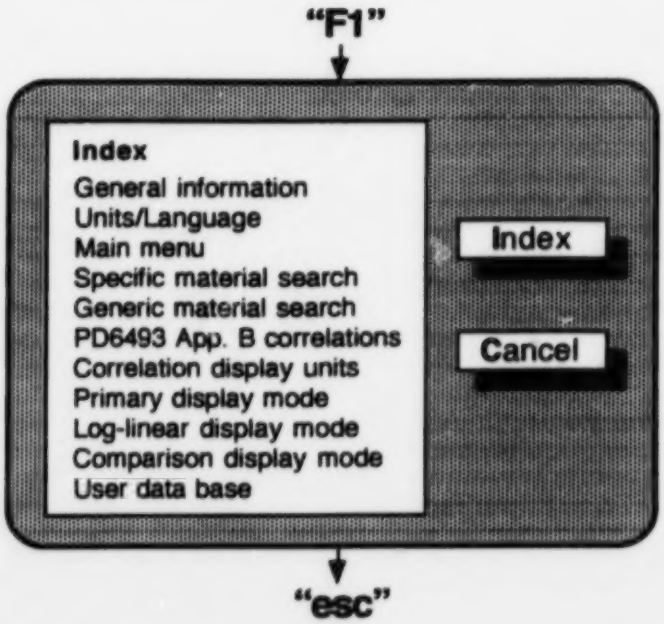

Fig.B.9 Help index options

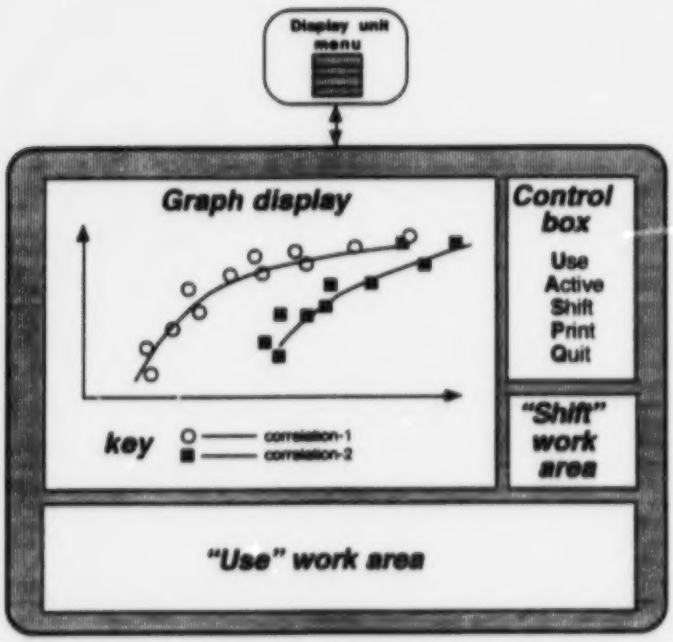

Fig.B.10 General display screen format

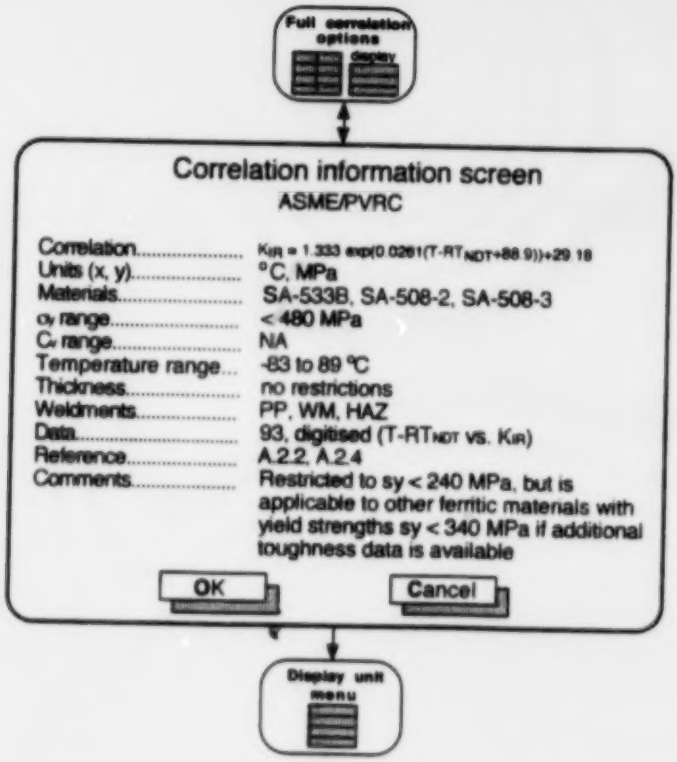

Fig.B.11 Example correlation information screen

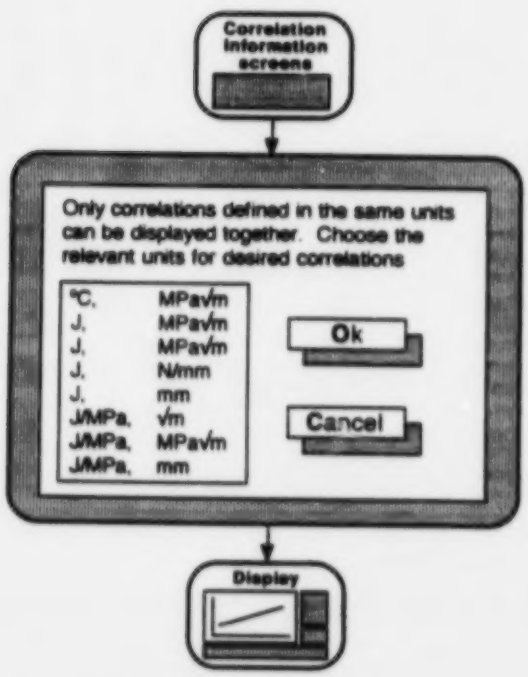

Fig.B.12 Display units menu

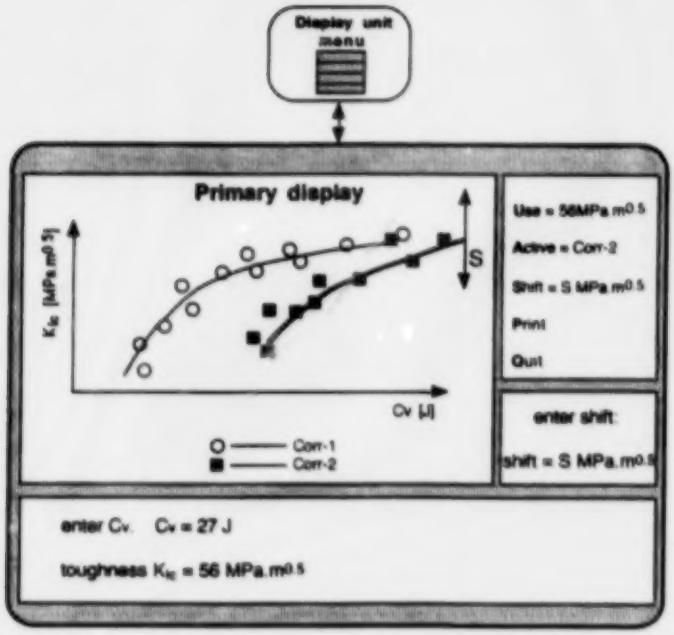

Fig.B.13 Primary Display Screen

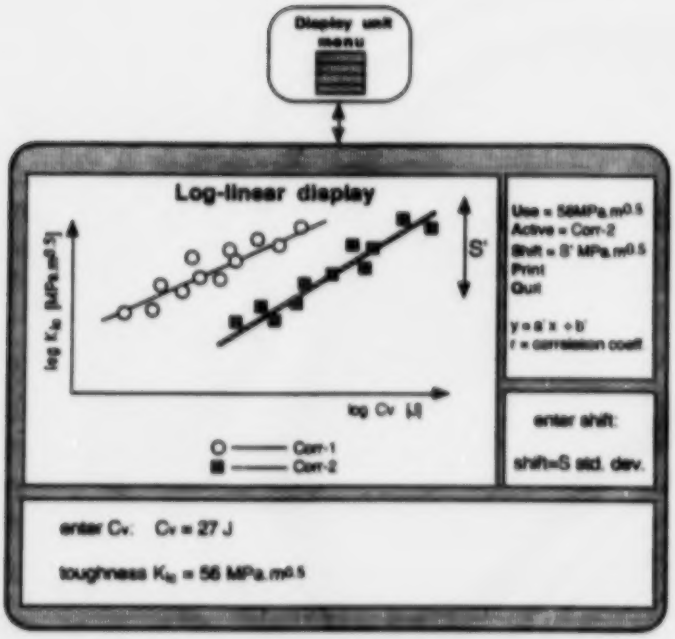

Fig.B.14 Log-linear Display Screen

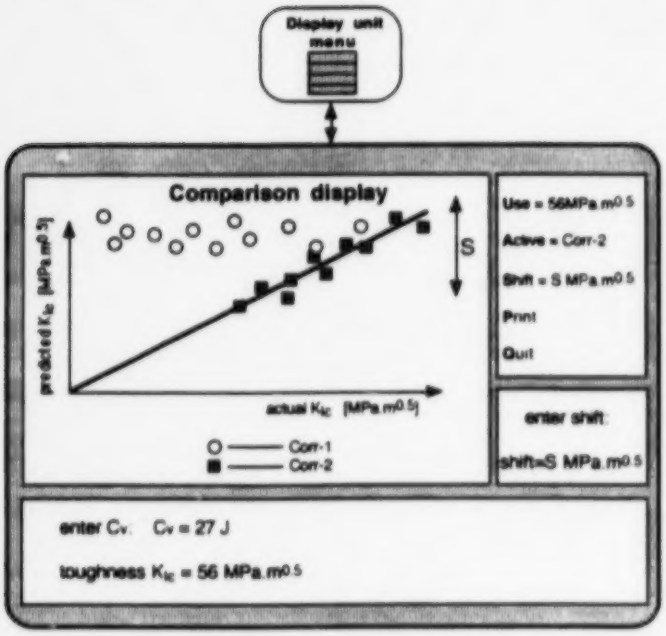

Fig.B.15 Comparison Display Screen